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(71) Applicant *(for all designated States except US)*: **UNIVERSITY OF DELAWARE** [US/US]; 210 Hullihen Hall, Newark, Delaware 19716 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **BARNETT, Allen M.** [US/US]; 19 Nivin Lane, Landenberg, Pennsylvania 19350 (US). **HONSBERG, Christiana Beatrice** [US/US]; 116 Eden Road, Landenberg, Pennsylvania 19350 (US). **BOWDEN, Stuart Graham** [US/US]; 116 Eden Road, Landenberg, Pennsylvania 19350 (US).

(74) Agents: **HAAS, Charles W.** et al.; Potter Anderson & Corroon LLP, P.O. Box 951, Wilmington, Delaware 19899-0951 (US).

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(54) Title: HIGH EFFICIENCY HYBRID SOLAR CELL

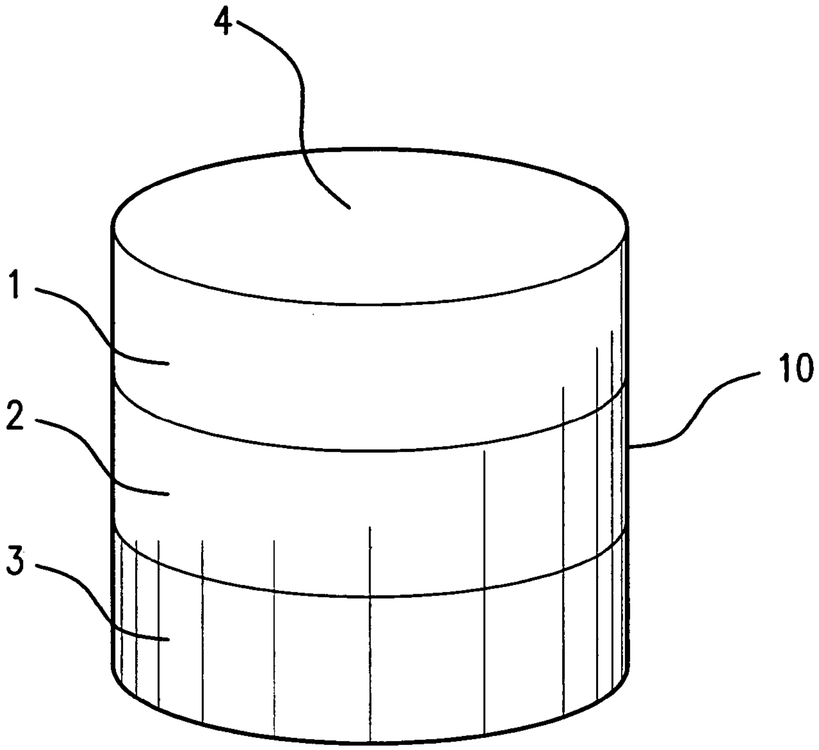


FIG.1

**(57) Abstract:** This invention relates to a high efficiency hybrid solar cell comprised of a dichroic mirror, a first cell stack comprising two cells, the first cell being a GaInP cell and the second cell being a GaAs cell and a second cell stack comprising three cells, the first cell being a Si cell, the second cell being a GaInAsP cell and the third cell being a GaInAs cell. The dichroic mirror provides a separation of the solar light into two spectral components, one component of light with photons of energy greater than or equal to Eg that impinges upon the first cell stack and one component of light with photons of energy < Eg that impinges upon the second cell stack.

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## TITLE

# HIGH EFFICIENCY HYBRID SOLAR CELL

This invention was made with Government support under Agreement W911NF-05-9-0005 awarded by the Government. The Government has certain rights in the invention.

The invention claimed herein was made pursuant to the Articles of Collaboration for the 50% Efficient Solar Cells Consortium formed pursuant to the Defense Advanced Research Projects Agency (DARPA) award to the University of Delaware October 1, 2005, W911NF-05-9-0005.

## FIELD OF THE INVENTION

This invention relates to a high efficiency hybrid solar cell suitable for use in both mobile and stationary applications.

## BACKGROUND OF THE INVENTION

Solar cell development has been in progress for over fifty years. One-junction silicon solar cells have received much attention over that period and are used in terrestrial photovoltaic applications. However, a one-junction silicon solar cell captures less than half of the theoretical potential for solar energy conversion with the best laboratory solar cells currently providing only about 24.7% efficiency. This limits the application of such cells.

High performance photovoltaic systems are required for both economic and technical reasons. The cost of electricity can be halved by doubling the efficiency of the solar cell. Many applications do not have the area required to provide the needed power using current solar cells.

Two types of solar cell architecture have been proposed for more efficient solar cells. One is a lateral architecture. An optical dispersion element is used to split the solar spectrum into its wavelength components. Separate solar cells are placed under each wavelength band and the cells are chosen so that they provide good efficiency for light of that wavelength band. Another architecture is a vertical one in which individual solar cells with different energy gaps are arranged in a stack. These are commonly referred to as cascade, tandem or multiple junction cells. The solar light is passed through the stack.

There is a need for the development of high efficiency solar cells and an architecture that enables the achievement of such solar cells.

## SUMMARY OF THE INVENTION

This invention provides a high efficiency hybrid solar cell comprising:

(a) a dichroic mirror operating at $E_g$ and positioned so that solar light impinges upon the dichroic mirror, wherein the dichroic mirror provides a separation of the solar light into two spectral components, one component of light with photons of energy $\geq E_g$ and one component of light with photons of energy $< E_g$, wherein one of these components is reflected by the dichroic mirror and one is transmitted by the dichroic mirror;

(b) a first cell stack comprising two cells, the first cell being a GaInP cell and the second cell being a GaAs cell, arranged vertically in descending order of their energy gaps with the first cell having the larger energy gap of the cells in the first cell stack, the first cell stack being positioned so that the component of light with photons of energy $\geq E_g$ impinges upon the surface of the first cell in the first cell stack, wherein the cells in the first cell stack each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap, wherein $E_g$ is equal to about the energy gap of the GaAs cell; and

(c) a second cell stack comprising three cells, the first cell being a silicon cell, the second cell being a GaInAsP cell and the third cell being a GaInAs cell, arranged vertically in descending order of their energy gaps with the first cell having the largest energy gap of the cells in the second cell stack, the second cell stack being positioned so that the component of light with photons of energy < $E_g$ impinges upon the surface of the first cell in the second cell stack, wherein the energy gap of each cell in the second cell stack is < $E_g$ and wherein cells in the second cell stack each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap.

Preferably, the dichroic mirror is a "cold" dichroic mirror.

## BRIEF DESCRIPTION OF THE FIGURES

Figure 1 shows a schematic drawing of a cell stack.

Figures 2A and 2B show the design of the demonstrated hybrid solar cell.

Figure 3 illustrates an embodiment of the hybrid solar cell with the with a dichroic mirror that reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$ and with the planes of the two cell stacks orthogonal.

Figure 4 illustrates another embodiment of the hybrid solar cell with a dichroic mirror that reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$ and with the two cell stacks in a coplanar configuration.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The instant invention provides a high efficiency hybrid solar cell with efficiency in excess of 30% and, preferably, up to and surpassing 40%. The hybrid solar cell is comprised of a dichroic mirror, a first cell stack comprising a GaInP cell and a GaAs cell and a second cell stack comprising a Si cell, a GaInAsP cell and a GaInAs cell.

The dichroic mirror operating at $E_g$ is positioned so that the solar light impinges upon the dichroic mirror. The so-called "cold" dichroic mirror reflects light with photons of energy $\geq E_g$ and transmits light with photons of energy $< E_g$. The so-called "hot" dichroic mirror transmits light with photons of energy $\geq E_g$ and reflects light with photons of energy $< E_g$. At the present stage of development of the two types of dichroic mirrors, the "cold" dichroic mirror is preferred. The dichroic mirror can be planar or curved.

"Cell" is used herein to describe the individual cells that are contained in the various stacks and that are generally referred to as solar cells. The term "solar cell" is used herein to describe the complete device.

As indicated above, as used herein, "arranged vertically in descending order of their energy gaps with the first cell having the largest energy gap of the cells in the stack" means that the cells in the stack are arranged sequentially with the first cell having the largest energy gap, the second cell directly below the first cell having the next largest energy gap, the third cell directly below the second cell having the third largest energy gap, etc. This arrangement of a cell stack is shown schematically in Figure 1. The cell stack 10 has three cells, 1, 2 and 3, with cell 1 being the first cell. The energy gaps of the three cells are such that $E_g^1 > E_g^2 > E_g^3$ where $E_g^1$ is the energy gap of cell 1, $E_g^2$ is the energy gap of cell 2 and $E_g^3$ is the energy gap of cell 3. Cell 1 will absorb the light with photons of energy $\geq E_g^1$ and transmit the light with photons of energy $< E_g^1$. Cell 2 will absorb the light with photons of energy $\geq E_g^2$ and transmit the light with photons of energy $< E_g^2$. Similarly with cell 3. The cells can be thought of as being in series optically. The cells convert the energy of the absorbed photons into electricity.

"Absorbed" as used herein means that a photon absorbed by the cell results in the creation of an electron-hole pair.

“The dichroic mirror operating at $E_g$” is used herein to mean that the dichroic mirror provides a separation of the solar light into two spectral components, one component of light with photons of energy ≥ $E_g$ and one component of light with photons of energy < $E_g$. One of these components is reflected by the dichroic mirror and one is transmitted by the dichroic mirror. A “cold” dichroic mirror reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$ and a “hot” dichroic mirror transmits light with photons of energy ≥ $E_g$ and reflects light with photons of energy < $E_g$. Typically the dichroic mirror will be positioned so that it is not perpendicular to the solar light. In this way the direction of the reflected light is not directly back toward the incoming solar light but is rather at an angle with respect to the direction of the solar light impinging on the dichroic mirror and the reflected light can more readily be arranged to impinge upon the appropriate cell stack. The transition from transmission to reflection occurs over a range of energies and corresponding wavelengths. The operating energy $E_g$ is taken as the midpoint of this transition region. For example, for a “cold” dichroic mirror, unless the transition is extremely sharp, it is recognized that some photons of energy > $E_g$ will be transmitted and some photons of energy < $E_g$ will be reflected. In the transition range, the majority of photons with energies greater than $E_g$ are reflected; the majority of photons with energies less than $E_g$ are transmitted. The above definition of “the dichroic mirror operating at $E_g$” should be understood and interpreted in terms of this recognition of the nature of the transition region. For a given dichroic mirror, the operating energy shifts to lower energies (higher wavelengths) as the dichroic mirror is rotated away from being perpendicular to the direction of incidence of the light beam impinging upon it and “the dichroic mirror operating at $E_g$” should be understood and interpreted to apply to the position in which the dichroic mirror is placed relative to the direction of the impinging light. A dichroic mirror is a multilayer structure, typically containing 20 or more alternate layers of two transparent oxides. A sharper transition requires more layers and higher cost.

"Hybrid" is used herein to describe the instant solar cell to indicate that it has neither a lateral architecture nor a vertical architecture but rather a combination of the two.

In a preferred embodiment, the high efficiency solar cell further comprises an optical element. The intensity or concentration of solar radiation striking a surface is 1X, the normal concentration. It is more difficult and more expensive to achieve high solar cell efficiency with 1X solar light than it is using solar light of higher concentrations. The purpose of the optical element is to collect and concentrate the light impinging upon it and direct the light upon the surface of the dichroic mirror. The optical element comprises a total internal reflecting concentrator that is a static concentrator. This static concentrator increases the power density of the solar light that can be utilized by the solar cell. It is a wide acceptance–angle concentrator that accepts light from a large portion of the sky. Unlike a tracking concentrator, the static concentrator is able to capture most of the diffuse light, much of which is in the blue to ultraviolet portion of the spectrum. This diffuse light makes up about 10% of the incident power in the solar spectrum. In practice, high levels of concentration are achieved by rejecting light from those portions of the sky in which the power density of the solar radiation is low throughout the year. In this way, concentrations of the solar light are increased by a factor of 10X or more. Higher concentrations are obtained if the position of the concentrator can be adjusted at some time during the year. Light is transmitted through one surface of the concentrator and that surface is adjacent to the surface of the dichroic mirror. "Solar light" is used herein to refer to the complete solar spectrum that impinges upon the surface of the dichroic mirror, no matter what the concentration. Preferably, the concentration is 10X or higher.

The light reflected and/or transmitted by the dichroic mirror can impinge directly upon the surface of the first cell in the appropriate stack. Alternatively, a reflecting mirror can be positioned so that light reflected and/or transmitted by the dichroic mirror is reflected by the reflecting mirror and directed to impinge upon the surface of the first cell in the appropriate stack, i.e., light with photons of energy $\geq E_g$ is directed to impinge upon the surface of the first cell in the first cell stack and light with photons of energy $< E_g$ is directed to impinge upon the surface of the first cell in the second cell stack. The dichroic mirror and the reflecting mirror can be incorporated in a single optical component.

The energy gaps of the respective cells will depend upon the exact composition of the cells and the method of preparation. Preferably, the energy gap of the GaInP cell is about 1.84 eV, the energy gap of the GaAs cell is about 1.43 eV, the energy gap of the Si cell is about 1.12 eV, the energy gap of the GaInAsP cell is in the range of from about 0.92 to about 0.95 eV and the energy gap of the GaInAs cell is in the range of from about 0.69 eV to about 0.74 eV.

A cell stack can be a monolithic structure. Alternatively, some or all of the cells can be prepared on individual substrates. For example, in the case of the second cell stack, the Si cell can be prepared on a substrate that is transparent to the light transmitted by the Si cell and the GaInAsP and GaInAs cells can be prepared as a monolithic tandem.

In one embodiment, the cells in one or both stacks are electrically connected in series to provide a single output for the stack. In a more preferred embodiment, all the individual cells in both stacks are contacted with individual electrical connections. This results in a substantial simplification of the solar cell and provides the opportunity to regulate the voltage across each cell at a value to provide optimum operation of the cell. The cells can be connected to a power combiner that provides a single electrical output for the solar cell at the desired voltage.

A GaInP cell with an energy gap of 1.84 eV and a GaAs cell with an energy gap of 1.43 eV are the preferred cells for the first cell stack. A two cell stack consisting of a GaInP/GaAs tandem cell can be prepared using, trimethyl gallium, trimethyl indium, phosphine, arsine and other precursors as described by K. A. Bertness et al., Appl. Phys. Lett. 65, 989 (1994). These cells differ from conventional GaInP/GaAs cells because they transmit photons of energy less than their energy gaps. The cells in the tandem cell made and demonstrated did not have individual electrical connections for the individual cells and were electrically in series. The cell with the best performance (fabricated by Emcore Corporation, Albuquerque, NM) had an active area of 0.1245 $cm^2$ and was operated at 25.1°C and 20X. The open circuit voltage, $V_{oc}$, was 2.631 V and the short circuit current, $I_{sc}$, was 41.59 mA. The maximum power, $P_{max}$, was 95.46 mW with Vmax = 2.334 V and Imax = 40.90 mA. The tandem cell exhibited a fill factor ($P_{max}/I_{sc}V_{oc}$) of 87.24% and an efficiency of 31.7%.

The first cell in the second cell stack is a silicon cell with an energy gap of 1.12 eV. Recent innovations have provided the opportunity to provide high performance silicon cells at a low cost. These include the use of thinner silicon junctions, the passivation of silicon surfaces by means other than insulators (M. Taguchi et al., Progress in Photovoltaics: Research and Applications, Vol 8, p 503-513 (2000)), the use of an optically transparent substrate and demonstrated high minority carrier lifetimes in n-type silicon (A. Cuevas et al., Appl. Phys. Lett. 81, 4952 (2002)). Silicon cells were fabricated using the deposition of the wide-energy gap semiconductor amorphous silicon to passivate the surfaces and achieve higher voltages and efficiencies. The structure used has a heterojuncton between crystalline silicon and amorphous silicon. The device performance is governed by the properties of the crystalline silicon substrate. The silicon cell design 20 is shown in Figures 2A and 2B. Figure 2A is a bottom view. As shown the cell is 4 mm wide and 9 mm long. There is a 1 mm wide metallized band 21 around three edges of the cell. The active cell area 22 is 8 mm x 2 mm. A cross-sectional view through "A-A" is shown in Figure 2B. This view shows the metallized band 21 around the bottom of the silicon cell 23. A transparent conductive oxide, indium tin oxide, 24 is shown on the top of the silicon cell 23. A metallized band 25 on top of the indium tin oxide layer has the same dimensions and shape as metallized band 21. The metallized bands 21 and 25 provide contacts for the electrical connections. Keeping all the metallization outside the active area of the cell ensures maximum transmittivity to the cells below it. The cell dimensions are small enough to allow adequate conduction along the indium tin oxide and through the cell bulk with minimal resistance losses. The silicon cells were tested with solar light filtered through GaAs. This simulated the light with photons of energy < $E_g$ that is directed to impinge upon the surface of the first cell in the second cell stack in the solar cell of the invention. The silicon cell with the best performance had an active area of 0.158 $cm^2$ and was operated at 25.0°C plus or minus 1.0°C and 20X filtered by GaAs. The $V_{oc}$ was 0.6900 V and $I_{sc}$ was 37.10 mA. The maximum power, $P_{max}$, was 15.76 mW with Vmax = 0.5084 V and Imax = 31.00 mA. The silicon cell exhibited a fill factor of 61.56% and an efficiency of 4.99%.

The second and third cells in the second cell stack, GaInAsP and GaInAs cells, can be prepared as described by R. J. Wehrer et al., Conference Record, IEEE Photovoltaic Specialists Conference, 2002, p 884-887. The cells demonstrated were prepared as a monolithic tandem in which the two cells are connected electrically independently. Since the cells were not serially connected electrically, a tunnel junction was not included between the cells. This simplified the growth procedure. An attempt was made to lower the energy gaps of the two cells to realize slightly higher conversion efficiency. The energy gap of the GaInAsP cell was 0.92 eV and the energy gap of the GaInAs cell was 0.69 eV. The 3-terminal electrical connection enabled the measurement of the performance of each cell independently. The performance of the cells was measured under an idealized silicon filter (1100 nm cutoff). The GaInAsP cell was under 21.4X light. The $V_{oc}$ was 0.400 V and the short circuit current density, $J_{sc}$, was 281 mA/cm$^2$. It exhibited a fill factor of 72% and an efficiency of 2.79%. The GaInAs cell was under 28.9X light. The $V_{oc}$ was 0.609 V and $I_{sc}$ was 167 mA/cm$^2$. It exhibited a fill factor of 73% and an efficiency of 3.46%. The combined efficiency of the two cells was 6.2%.

The total efficiency of the two demonstrated cell stack components was 42.9%.

The cell stacks can be mounted on one or more mounting boards depending on the configuration of the particular embodiment. A silicon cell that would serve as a scavenger cell to absorb light not otherwise absorbed and convert it into electricity can be placed adjacent to or contiguous to the last cell in one or both stacks. The silicon scavenger cell would have a larger cross-section than the cells in the cell stack, typically at least about 10 times that of the cells in the cell stack. Some of the light intercepted by a scavenger cell is light that is not incident on the cell stack, reflected light, light not absorbed by cells in the stack, for example, by the cells in the first cell stack and diffuse light that did not impinge on the cell stacks. Scavenger silicon cells can be electrically connected in series or in parallel or connected independently.

Light reflected from the surfaces of cells is a potential source of decreased solar cell efficiency. An anti-reflection coating can be applied to the surfaces of any of the cells upon which light impinges to minimize this loss.

In one embodiment the light reflected and transmitted by the dichroic mirror propagates in air before impinging on the respective cell stacks. In another embodiment one or more transparent solids can be provided for these lights to propagate through.

In Figures 3 and 4, the same numbers are used to identify the same entities. For, simplicity, the various light beams are represented by one light ray.

Figure 3 illustrates an embodiment of the hybrid solar cell. The solar cell 30A is comprised of "cold" dichroic mirror 31, a first cell stack 32 and a second cell stack 33. The first cell stack 32 contains two cells, a GaInP cell 34 and a GaAs cell 35. The second cell stack 33 contains three cells, a Si cell 36, a GaInAsP cell 37 and a GaInAs 38. The dichroic mirror 31 operates at $E_g$ and reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$. Solar light 41 impinges upon the dichroic mirror 31 which is positioned at an angle of about 45° with respect to the direction of the solar light 41. Light 42 with photons of energy ≥ $E_g$ is reflected by the dichroic mirror and impinges upon the surface of the first cell 34 of the first cell stack 32. Cells 34 and 35 each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap. Light 43 with photons of energy < $E_g$ is transmitted by the dichroic mirror and impinges upon the surface of the first cell 36 of the second cell stack 33. Cells 36, 37 and 38 each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap. Figure 3 shows an embodiment in which the hybrid solar cell further comprises Si scavenger cells 39 and 40. Si scavenger cell 39 is shown contiguous to cell 35 and Si scavenger cell 40 is shown contiguous to cell 38. Light in their respective areas which does not impinge on the first cell stack 33 and the second cell stack 34 impinges on the Si scavenger cells 39 and 40.

Figure 4 illustrates another embodiment of the hybrid solar cell. The solar cell 30A is comprised of "cold" dichroic mirror 31, a first cell stack 32, a second cell stack 33 and a reflecting mirror 44. The first cell stack 32 contains two cells, a GaInP cell 34 and a GaAs cell 35. The second cell stack 33 contains three cells, a Si cell 36, a GaInAsP cell 37 and a GaInAs 38. The dichroic mirror 31 operates at $E_g$ and reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$. Solar light 41 impinges upon the dichroic mirror 31 which is positioned so that light is reflected as shown in Figure 4. Light 42 with photons of energy ≥ $E_g$ is reflected by the dichroic mirror and impinges upon the surface of the first cell 34 of the first cell stack 32. Cells 34 and 35 each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap. Light 43 with photons of energy < $E_g$ is transmitted by the dichroic mirror and is reflected by the reflecting mirror 44. The reflected light 43 impinges upon the surface of the first cell 36 of the second cell stack 33. Cells 36, 37 and 38 each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap. Figure 4 shows an embodiment in which the hybrid solar cell further comprises Si scavenger cells 39 and 40. Si scavenger cell 39 is shown contiguous to cell 35 and Si scavenger cell 40 is shown contiguous to cell 38. Light in their respective areas which does not impinge on the first cell stack 33 and the second cell stack 34 impinges on the Si scavenger cells 39 and 40. In this configuration the cell stacks and the Si scavenger cells can readily be supported on the same mounting board.

## CLAIMS

What is claimed is:

1. A high efficiency hybrid solar cell comprising:

(a) a dichroic mirror operating at $E_g$ and positioned so that solar light impinges upon the dichroic mirror, wherein the dichroic mirror provides a separation of the solar light into two spectral components, one component of light with photons of energy $\geq E_g$ and one component of light with photons of energy $< E_g$, wherein one of these components is reflected by the dichroic mirror and one is transmitted by the dichroic mirror;

(b) a first cell stack comprising two cells, the first cell being a GaInP cell and the second cell being a GaAs cell, arranged vertically in descending order of their energy gaps with the first cell having the larger energy gap of the cells in the first cell stack, the first cell stack being positioned so that the component of light with photons of energy $\geq E_g$ impinges upon the surface of the first cell in the first cell stack, wherein the cells in the first cell stack each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap, wherein $E_g$ is equal to about the energy gap of the GaAs cell; and

(c) a second cell stack comprising three cells, the first cell being a Si cell, the second cell being a GaInAsP cell and the third cell being a GaInAs cell, arranged vertically in descending order of their energy gaps with the first cell having the largest energy gap of the cells in the second cell stack, the second cell stack being positioned so that the component of light with photons of energy $<$ $E_g$ impinges upon the surface of the first cell in the second cell stack, wherein the energy gap of each cell in the second cell stack is < $E_g$ and wherein cells in the second cell stack each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap.

2. The high efficiency hybrid solar cell of claim 1, wherein the dichroic mirror reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$.

3. The high efficiency hybrid solar cell of claim 1, wherein the energy gap of the GaInP cell is about 1.84 eV, the energy gap of the GaAs cell is about 1.43 eV, the energy gap of the Si cell is about 1.12 eV, the energy gap of the GaInAsP cell is in the range of from about 0.92 to about 0.95 eV and the energy gap of the GaInAs cell is in the range of from about 0.69 eV to about 0.74 eV.

4. The high efficiency hybrid solar cell of claim 3, wherein $E_g$ is about 1.43 eV.

5. The high efficiency hybrid solar cell of claim 4, wherein the dichroic mirror reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$.

6. A method for converting solar light into electrical power, the method comprising:

   (a) positioning a dichroic mirror so that solar light impinges onto the surface of the dichroic mirror and the dichroic mirror separates the light into two spectral components of light, one component of light with photons of energy ≥ $E_g$ and one component of light with photons of energy < $E_g$;

   (b) positioning a first cell stack comprising two cells, the first cell being a GaInP cell and the second cell being a GaAs cell, arranged vertically in descending order of their energy gaps with the first cell having the larger energy gap of the cells in the first cell stack, the first cell stack being positioned so that the component of light with photons of energy ≥ $E_g$ impinges upon the surface of the first cell in the first cell stack, wherein the cells in the first cell stack each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap, wherein $E_g$ is equal to about the energy gap of the GaAs cell; and

(c) positioning a second cell stack comprising three cells, the first cell being a Si cell, the second cell being a GaInAsP cell and the third cell being a GaInAs cell, arranged vertically in descending order of their energy gaps with the first cell having the largest energy gap of the cells in the second cell stack, the second cell stack being positioned so that the component of light with photons of energy < $E_g$ impinges upon the surface of the first cell in the second cell stack, wherein the energy gap of each cell in the second cell stack is < $E_g$ and wherein cells in the second cell stack each absorb light with photons of energy greater than or equal to their energy gap and are transparent to and transmit light with photons of energy less than their energy gap.

7. The method of claim 6, wherein the dichroic mirror reflects light with photons of energy ≥ $E_g$ and transmits light with photons of energy < $E_g$.

8. The method of claim 7, wherein the energy gap of the GaInP cell is about 1.84 eV, the energy gap of the GaAs cell is about 1.43 eV, the energy gap of the Si cell is about 1.12 eV, the energy gap of the GaInAsP cell is in the range of from about 0.92 to about 0.95 eV and the energy gap of the GaInAs cell is in the range of from about 0.69 eV to about 0.74 eV.and $E_g$ is about 1.43 eV.

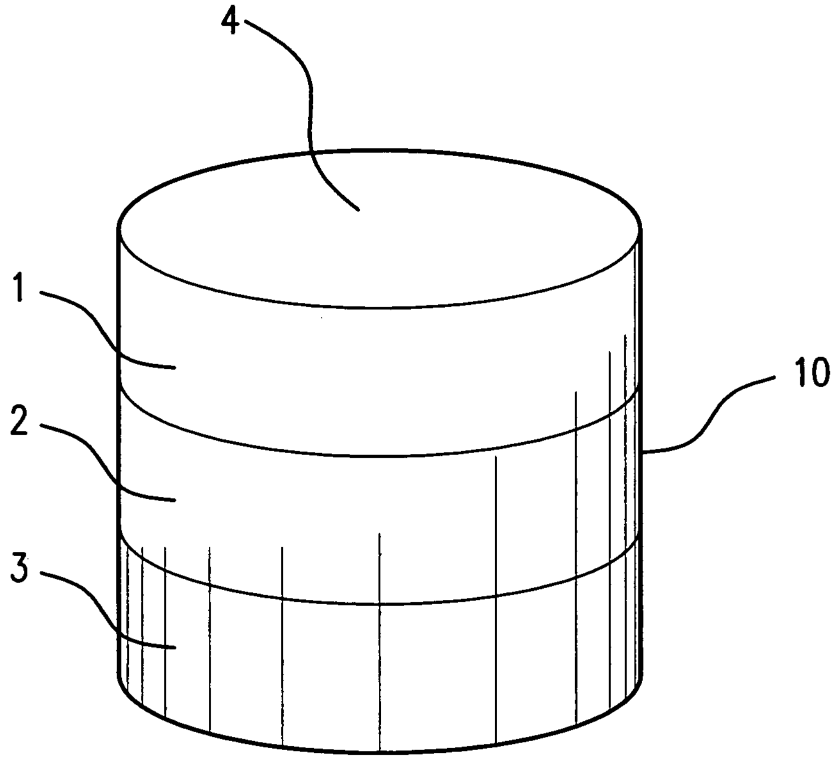


FIG.1

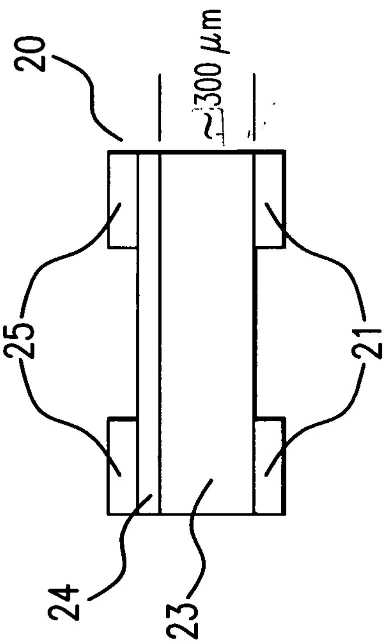


FIG.2B

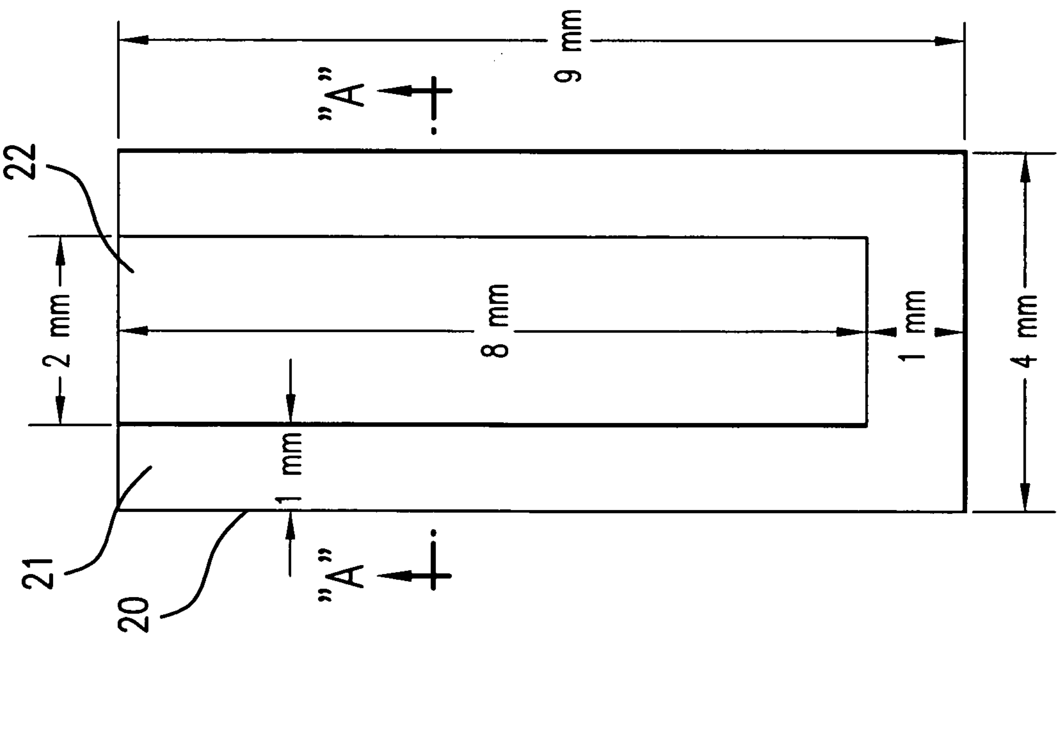


FIG.2A

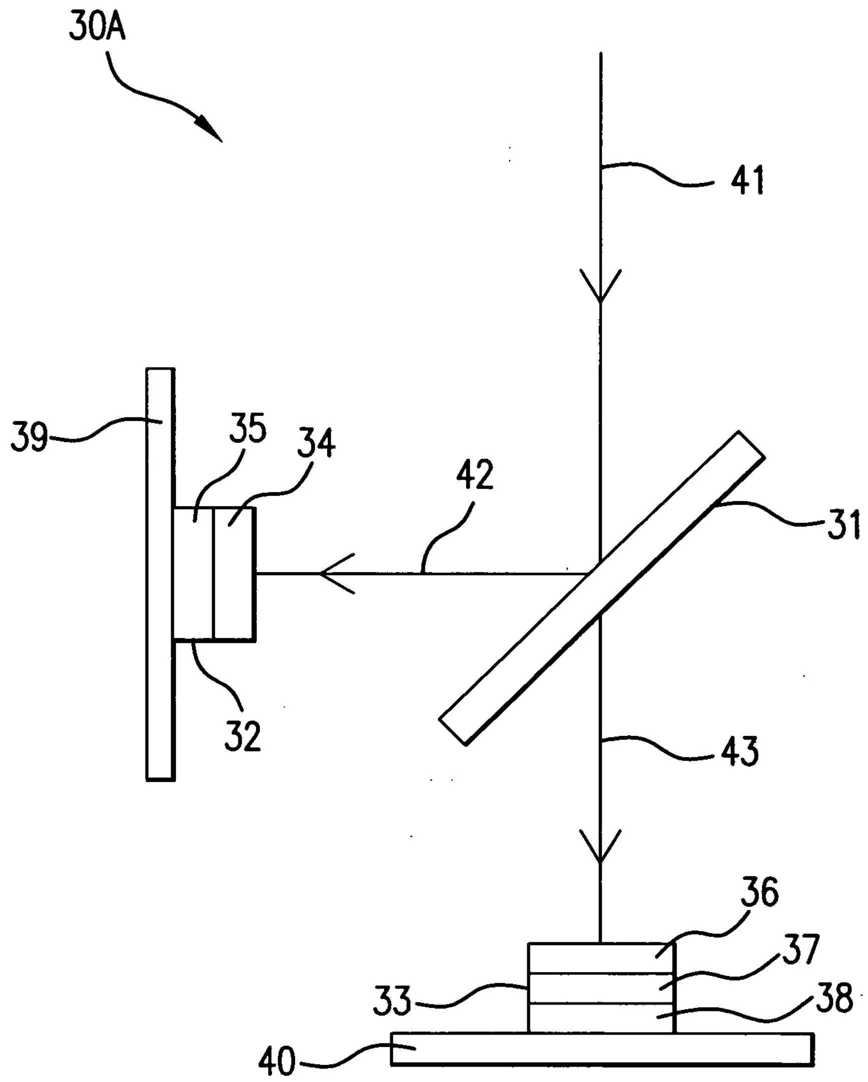


FIG.3

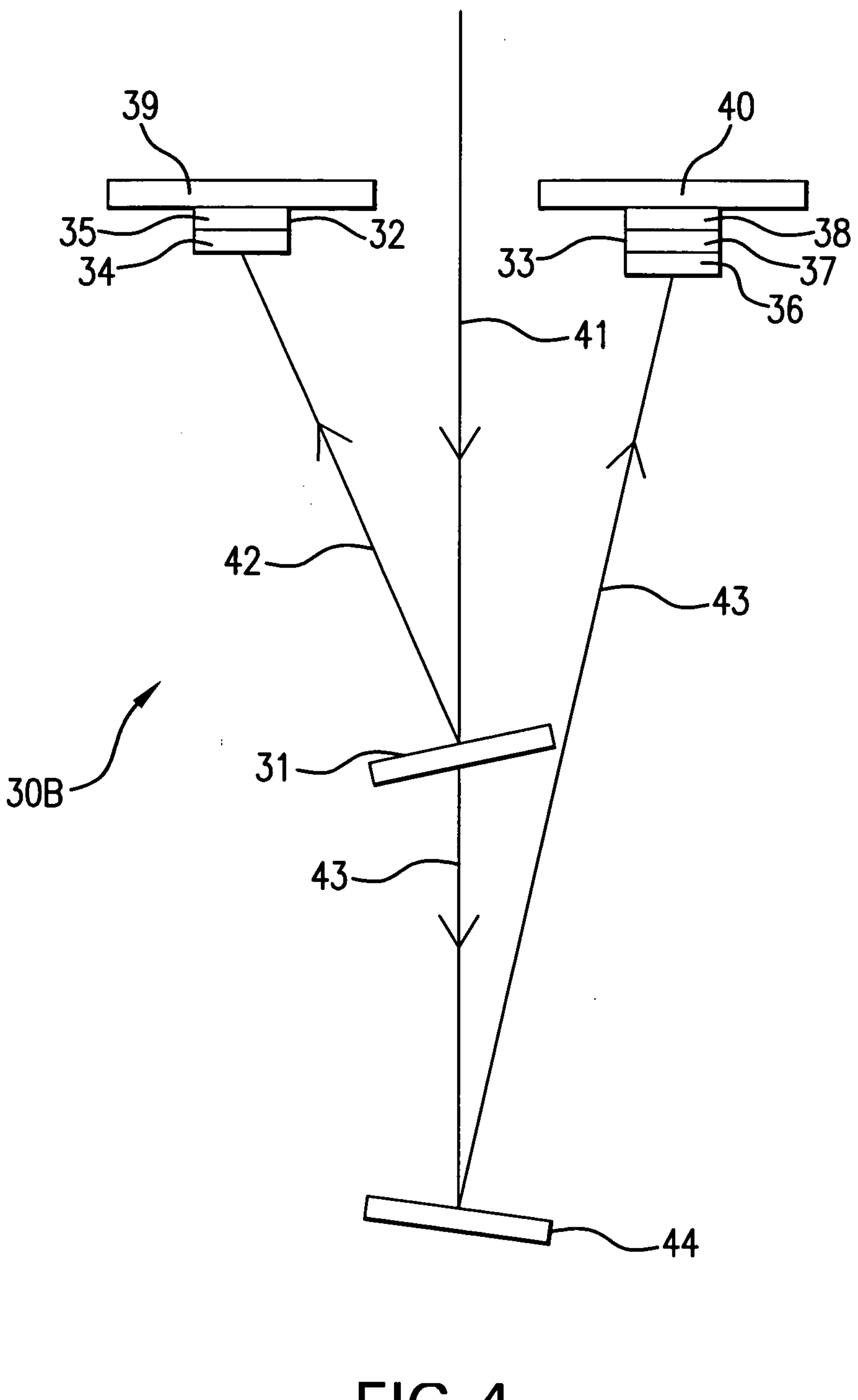


FIG.4