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MONOLITHIC CASCADE-TYPE SOLAR CELLS

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Translation of "Monorishikku kasukeido-kei taiyo-denchi," Nippon Telegraph and Telephone Public Corp., Jpn. Kokai Tokkyo Koho, Japan Patent 59-172780, pp. 1-5, September 29, 1984

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16. Abstract

A solar cell consists of a semiconductor base, a bottom cell having a band-gap energy of E_1, and a top cell having a band-gap energy of E_2, where $0.96 \leq E_1 \leq 1.36$ eV and $(0.80\ E_1 + 0.77)$ eV $\leq E_2 \leq (0.80\ E_1 + 0.92)$ eV. Thus, a monolithic cascade-type solar cell was prepared with an n^+-type GaAs base, a GaInAs bottom solar cell, and a GaAlInAs top solar cell. The surface of the cell was coated with a SiO antireflection film. The efficiency of the cell was 32%.

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(54) Monolithic Cascade-Type Solar Cell

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MONOLITHIC CASCADE-TYPE SOLAR CELL

Detailed Specifications

Name of Invention /341*

Monolithic cascade-type solar cell

Scope of Patent Claim

A monolithic cascade-type solar cell distinguished by a semiconductor base upon which are placed a bottom cell made of a semiconductor with a band-gap energy of E_1 and a top cell made of a semiconductor with a band-gap energy of E_2, the aformentioned bottom cell's band-gap energy having a range of $0.96\ \mathrm{eV} \leq E_1 \leq 1.36\ \mathrm{eV}$ and the aformentioned top cell's band gap energy having a range of $0.80\ E_1 + 0.77\ \mathrm{eV} \leq E_2 \leq 0.80\ E_1 + + 0.92\ \mathrm{eV}$.

Detailed Explanation of Invention

This invention concerns a high-efficiency monolithic cascade-type solar cell.

The conversion efficiency of solar cells is largely a function of the band-gap energy of their semiconductor layers. In a solar cell which utilizes a single-layer transformation conversion semiconductor, even if a semiconductor with the highest band-gap energy (approximately 1.4 eV) is used, the highest theoretical transformation efficiency is about 25%. The reason for this is that the rays within the spectrum of sunlight

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*Numbers in the margin indicate pagination in the foreign text.

which represent energy below the range of the semiconductor band pass through the band and cannot be utilized. This is what gave rise to the proposal for a monolithic cascade-type solar cell which be more efficient. This type of arrangement consists of a semiconductor with a lower band-gap energy (E_1), called the [bottom solar]* cell and a semiconductor with a higher band-gap energy (E_2), called the top solar cell, with both cells mounted on the same substrate. The conversion efficiency of this sort of solar cell varies considerably with the selection of E_1 and E_2. According to theoretical calculations for conversion efficiency made by M. F. Lamorte and D. H. Abbot [IEEE Trans. Electron Devices ED - 27, 231, (1981)], when E_1 = 0.95 eV and E_2 = 1.62 eV, a maximum efficiency of 31.5% is attained, and any departure from these specifications brings about a marked decline in /342
efficiency. Up to the present, monolithic cascade-type solar cells have all been made according to these specifications. As indicated above, both E_1 and E_2 had single values which yielded maximum efficiency, and, consequently, the selection of materials and the structural design for solar cells were severely limited.

The inventors of this device made detailed theoretical calculations concerning the conversion efficiency of solar cells and discovered that a higher maximum efficiency could be attained by specifications for E_1 and E_2 which represented a departure from the current standard. This invention, which is based upon the results of those calculations, intends to provide a monolithic cascade-type solar cell which has a higher conversion efficiency.

*[Translator's Note: These words did not appear in the original text, apparently an error, since they are required by the context.]

Accordingly, in this invention the monolithic cascade-type solar cell, which consists of a bottom solar cell with band-gap energy of E_1 and a top solar cell with band-gap energy of E_2, both mounted on a substrate, is characterized by having band-gap energy ranges of $0.96 \text{ eV} \leq E_1 \leq 1.36 \text{ eV}$ for the bottom cell and $0.80\ E_1 + 0.77 \text{ eV} \leq E_2 \leq 0.80\ E_1 + 0.92 \text{ eV}$ for the top cell.

Using this invention not only allows a higher conversion efficiency than is currently available with monolithic cascade-type solar cells; the wider range of possible values for E_1 and E_2 create the additional advantage of greater freedom in selection of materials.

A more detailed explanation of the invention follows:

The report by M. F. Lamorte and D. A. Abbott concerning theoretical calculations for conversion efficiency of the monolithic cascade-type solar cell shows the calculations themselves, but tells nothing about procedures, hypotheses, etc.

The inventors of this invention made their calculations on the following bases:

The spectrum of sunlight used as a basis is AMO (Air Mass Zero). Furthermore, rays with wavelength less than 0.3 μ, that is, energy more than 4.1 eV, are not utilized. The top solar cell and the bottom solar cell have band-gap energies of E_2 and E_1, respectively; rays ranging from 4.1 eV to E_2 are used in the top cell, while those ranging from E_2 to E_1 are used in the bottom cell. Consequently, the short-circuit current density of the top solar cell J_{sc2} was found by taking the photon count between 4.1 eV and E_2, and multiplying it by the collecting efficiency of the carrier and the electron charge q. Similarly, the short-circuit current density of the bottom cell J_{sc1} was calculated by multiplying the photon count between E_2 and E_1 by the collecting efficiency of the carrier and q. Here, the ideal carrier efficiency for either junction would be 100%. Next, the current densities J_{o2} and J_{o1} are calculated for the pn junction diode, which functionally divides lower and upper cells. As is well known, this can be found simply by using the intrinsic carrier [illegible word; might be "density"] for the top semiconductor. Using values for J_{sc2}, J_{sc1}, J_{o2} and J_{o1} which we have calculated in this manner, the relationship of output current density J and output voltage V can be expressed in the following manner for the top and bottom cells:

$$J = J_{sc2} - J_{o2} \{\exp(qV/nKT) - 1\} \quad (1)$$

for the top cell; and, similarly, for the bottom cell

$$J = J_{sc1} - J_{o1} \{\exp(qV/nKT) - 1\} \quad (2)$$

Here n designates the diode element which, in the case of an ideal diode, would be 1. Here n = 1. Also, q is the electron charge, k is the Boltzmann constant, and T is the absolute temperature.

Figure 1 is a graphic representation of Formula (1) and Formula (2) with (a) showing the top cell and (b) the bottom cell. First, output voltage where J = 0 for Formulas (1) and (2), respectively, was designated as open end voltage. In the monolithic cascade-type solar electric field, where top and bottom cells are connected in series, there must be an equal amount of current flowing through both top and bottom cells, and so the electric output P of the monolithic cascade-type /343 solar cells is $J_c \times (V_2 + V_1)$, as can be seen from Figure 1. Here V_2 and V_1 are the respective output voltages for the top and bottom cells when a common current density J_c is attained in both cells. When calculating P with a frequently changing J_c, the maximum value P_m can easily be found. Designating the values for

J_c, V_2, and V_1, which yield P_{jm} as J_{cm}, V_{2m}, and V_{1m}, respectively, the formula becomes $P_m = J_{cm}(V_{2m} + V_{1m})$. In actual monolithic cascade-type solar cells, since top and bottom cells are electrically connected in series and a tunnel junction layer is used, there are decreased voltage and an accompanying loss of power within this layer. In this case, voltage reduction in the tunnel junction was determined to be 0.05 V. Thus, actual maximum electric output P'_m is expressed as $P'_m = J_{cm} \times (V_{2m} + + V_{1m} - 0.05\ V)$. Furthermore, the conversion efficiency η of monolithic cascade-type solar cells is calculated as P'_M/P_I, using P_I as the total input of sunlight.

In this manner, by only varying E_2 and E_1 and finding η, a "map" of values for η as a function of variations in E_2 and E_1 was made. Results were such that, when E_2 = 1.62 eV and E_1 = 0.95 eV, η = 31.5%, which is consistent with other results reported up to the present. But what drew attention was that the existence of a combination of values for E_1 and E_2 which would produce comparatively higher efficiency had been clearly shown. Furthermore, that combination is not a single point, but a comparatively wide range. That is to say, it is clear that values for E_2 and E_1, which satisfy the conditions $0.96\ eV \leq \leq E_1$, $E_1 \leq 1.36$ eV and $0.08\ E_1 + 0.77\ eV \leq E_2 \leq 0.08\ E_1 + 0.92$ eV make 32% conversion efficiency possible. Any materials which can satisfy the requirements stated above for E_2 and E_1 and which can form grid-type junctions may be used for the joined semiconductor layers which form the top and bottom cells in this invention. Examples are: (a) GaInAs compounds (E_1) - GaAlInAs compounds (E_2; (b) GaInAsP compounds (E_1) - GaAlInP compounds (E_2); (c) GaAlInAs compounds (E_1) - GaAlInP compounds (E_2); (d) GaInAsP compounds (E_1) - AlInP compounds (E_2); and (e) GaAlInAs compounds (E_1) - AlInP compounds (E_2).

Furthermore, any material from these groups (GaAs of InP, for example) may be selected for small items such as the semiconductor layer or the uneven grid in the bottom cell. Use of these materials in the manufacture of monolithic cascade-type solar cells results in extremely high conversion efficiency, as will be clearly shown in the experiments below, where the effectiveness of the inventors' theoretical calculations is confirmed. A detailed description of the experiments follows.

<u>Experiment 1</u>

Figure 2 shows a cross-section of the monolithic cascade-type solar cell which is an application of this invention. It was constructed from the materials listed under (a) above. 1 is the N+ - GaAs substrate; 2 is the N - $Ga_{0.04}$ $In_{0.06}$ As layer; 3 is the N - $Ga_{0.08}$ $In_{0.12}$ layer; 4 is a $Ga_{0.83}$ $In_{0.17}$ As layer which contains a Pn junction; 5 is a $(Ga_{0.56}$ $Al_{0.44})_{0.95}$ $In_{0.05}$ As layer containing a P^+n^+ junction; 6 is a $(Ga_{0.56}$ $Al_{0.04})_{0.95}$ $In_{0.05}$ As layer containing a Pn junction; 7 is a P^+ - $(Ga_{0.42}$ $Al_{0.56})_{0.95}$ $In_{0.05}$ layer; 8 is a comb-type ohm electrode; 9 is a surface-type ohm electrode; 10 is an anti-reflection layer.

The N - $Ga_{0.04}$ $In_{0.06}$ As layer and the N - $Ga_{0.08}$ $In_{0.17}$ As layer 3 are placed so as to mitigate the grid unevenness which accompanies the variation in grid constant between the N^+ - GaAs substrate (1) and the $Ga_{0.87}$ $In_{0.17}$ As layer (4), and have no integral role in the functioning of the cell. The $Ga_{0.83}$ $In_{0.17}$ As layer (4), which has a band-gap energy of 1.07 eV, functions as the bottom cell, the $(Ga_{0.56}$ $Al_{0.44})_{0.05}$ $In_{0.05}$ As layer (6), which has a band-gap energy of 1.70 eV, functions as the top cell. The $(Ga_{0.56}$ $Al_{0.44})_{0.95}$ $In_{0.05}$ As layer 5 functions as a tunnel junction which connects top and bottom cells electrically in a series. The P^+ - $(Ga_{0.42}$ $Al_{0.58})_{0.95}$ $In_{0.05}$ As layer 7 has a band-gap energy 0.2 eV larger than the $(Ga_{0.56}$ $Al_{0.44})_{0.95}$ $In_{0.05}$ As layer 6 and functions as a device for preventing <u>/344</u> elimination of the carrier due to surface recombination on layer 6. In the manufacture of this type of monolithic cascade-type solar cell, once the semiconductor layers have been formed by epitaxial growth on the N^+ - Ga As substrate, the comb-type ohm-style electrode layer 8 and the surface-type ohmic electrode layer 9 are formed, and, finally, the cell is completed by forming an anti-reflection layer 10. Epitaxial growth of semiconductor layers is carried out by liquid-phase epitaxis (LPE), vapor-phase epitaxis (VPE), molecular-based epitaxis (MBE), or [illegible word] metallic [illegible word] vapor deposit (MOCVD). In this instance a monolithic cascade solar cell was made by forming the semiconductor layers using MBE. The comb-type ohmic electrode 8 was made of Au-Zn, the surface-type ohmic electrode 9 was made with Au-Ge, and the anti-reflection layer 10 was made of SiO, and at AMO (Air MAss Zero) efficiency of 32% was achieved, clearly showing the efficacy of this invention.

<u>Experiment 2</u>

Among the materials described in (b) through (e) above, which are used to form semiconductor layers or substrates, InP produces a relatively low amount of grid unevenness. Furthermore, GaInP is suitable for forming the intermediate layers that mitigate the unevenness which accompanies variation in grid constant between a substrate and a semiconductor layer which contain InP. Next, a description of a monolithic cascade-type solar cell made with material type (b) will be given: intermediate layers of $N - Ga_{0.10} In_{0.90} P$ and $N - Ga_{0.20} In_{0.80} P$ are formed on a N^+ - InP substrate, after which the following layers are added in sequence: a bottom cell of $Ga_{0.65} In_{0.35} As_{0.93} P\cdot_{0.07}$ which contains a Pn junction and has band-gap energy of 0.97 eV; a tunnel junction layer composed of a $(Ga_{0.71} Al_{0.29})_{0.20} In_{0.08} P$ containing a P^+N^+ junction; a top cell of $(Ga_{0.71} A_{0.29})_{0.20} In_{0.80} P$ with a Pn junction and band-gap energy of 1.60 eV; and a cover layer of $P^+ - Al_{0.20} In_{0.80} P$. Next, as shown in Figure 2

[Note: The original text reads "Figure 1," but this does not fit the context], a comb-style ohmic electrode, a surface ohmic electrode and an anti-reflection layer are formed. The solar cell made in this way exhibited 31% conversion efficiency under conditions of AMO. In this experiment the bottom cell was composed of Ga Al In P, though it is clear that the same high efficiency could have been achieved using Ga Al In As or Ga Al In P in place of Ga In As P.

As explained above, the monolithic cascade-type solar cell which pertains to this invention not only attains a higher conversion efficiency than other types used to date, but also widens the range of feasible matches between E_1 and E_2, thus widening the variety of materials which can be used.

Explanation of Illustrations

Figure 1 shows the relationship between output current density J and output voltage V in the upper and lower cells of the monolithic cascade-type solar cell. Part (a) shows the top cell, and part (b) shows the bottom cell. Figure 2 shows a cross-section of a monolithic cascade-type solar cell formed according to this invention.

1: N^+ - Ga As substrate

2: N - $Ga_{0.94}$ $In_{0.06}$ As layer

3: N - $Ga_{0.88}$ $In_{0.12}$ layer

4: $Ga_{0.83}$ $In_{0.17}$ As layer containing Pn junction

5. $(Ga_{0.56}$ $Al_{0.44})_{0.95}$ As layer containing P^+N^+ junction

6. $(Ga_{0.56}$ $Al_{0.44})_{0.95}$ $In_{0.05}$ As layer containing Pn junction

7. P^+ - $(Ga_{0.42}Al_{0.58})_{0.95}In_{0.05}As$ layer

8. Comb-style ohmic electrode

9. Surface ohmic electrode

10. Anti-reflection layer

Applicant's Legal Representatives: M. Amemiya

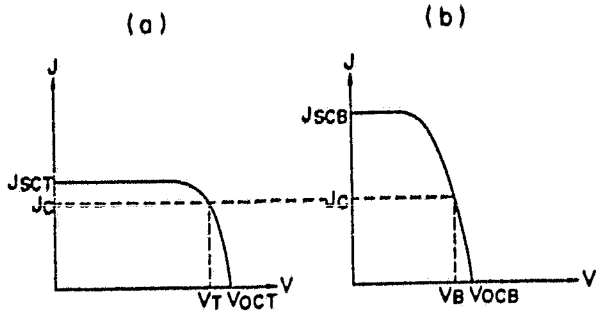

Figure 1

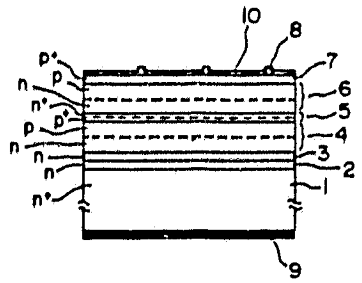

Figure 2