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(54) **Title**: TANDEM SOLAR CELL INTEGRATED IN A DOUBLE INSULATING GLASS WINDOW FOR BUILDING INTEGRATED PHOTOVOLTAIC APPLICATIONS

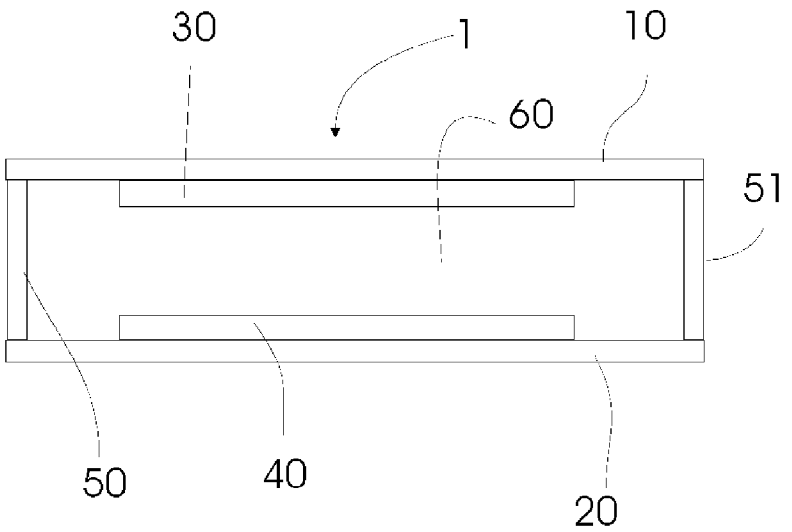

Fig. 1

(57) **Abstract**: The present invention relates to an insulated window having two solar cells on each window pane so that the window can be used to generate electric energy. One solar cell is an amorphous Si-Cell, the other either an amorphous or microcrystalline Si-Cell.

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Description

TANDEM SOLAR CELL INTEGRATED IN A DOUBLE INSULATING GLASS WINDOW FOR BUILDING INTEGRATED PHOTOVOLTAIC APPLICATIONS

Technical Field

[0001] This invention relates to refers to addresses solar cells or solar modules of the so-called tandem type, i.e. stacked arrangements of photovoltaic absorber devices.

Background Art

[0002] Solar cells, also known as photovoltaic cells, are semiconductors that convert electromagnetic energy, such as light or solar radiation, directly to electricity. These semiconductors are characterized by energy bands gaps between their valence electron bands and their conduction electron bands, so that free electrons cannot ordinarily exist or remain in these band gaps. However, when light is absorbed by the materials that characterize the photovoltaic cells, electrons that occupy low-energy states are excited and jump the band gap to unoccupied higher energy states. Thus, when electrons in the valence band of a semiconductor absorb sufficient energy from photons of solar radiation, they jump the band gap to the higher energy conduction band.

[0003] Electrons excited to higher energy states leave behind them unoccupied low-energy positions which are referred to as holes. These holes may shift from atom to atom in the crystal lattice and the holes act as charge carriers, in the valence bond, as do free electrons in the conduction band, to contribute to the crystal's conductivity. Most of the photons that are absorbed in the semiconductor produce such electron-hole pairs. These electron-hole pairs generate photocurrent and, in the presence of a built-in field, the photovoltage of the solar cells.

[0004] Electron hole pairs produced by the light would eventually recombine, and convert to heat or a photon, unless prevented from doing so. To prevent this phenomenon, a local electric field is created in the semiconductor by doping or interfacing dissimilar materials to produce a space charge layer. The space charge layer separates the holes and electrons for use as charge carriers. Once separated, these collected hole and electron charge carriers produce a space charge that results in a voltage across the junction, which is the photovoltage. If these separated hole and charge carriers are allowed to flow through an external load, they would constitute a photocurrent.

[0005] In practice, the semiconductor must be designed with a small band gap so that even photons from lower energy radiation can excite electrons to jump the band gap, but, in doing so, there are at least two negative effects that must be traded.

[0006] First, the small band gap results in a low photovoltage device, and thus low power output occurs. Secondly, the photons from higher energy radiation will produce many hot carriers with much excess energy that will be lost as heat upon immediate thermalization of these hot carriers to the edge of the conduction band.

[0007] On the other hand, if the semiconductor is designed with a larger band gap to increase the photovoltage and reduce energy loss caused by thermalization of hot carriers, then the photons from lower energy radiation will not be absorbed. Therefore, in designing conventional single junction solar cells, it is necessary to balance these considerations and try to design a semiconductor with an optimum band gap, realizing that in the balance, there has to be a significant loss of energy from both large and small energy photons.

[0008] Materials, such as silicon with a band gap of 1.1 eV, are relatively inexpensive and are considered to be good solar energy conversion semiconductors for conventional single junction solar cells. Nevertheless, a need exists for a device that can capture and use a larger range of photon energies from the solar radiation spectrum, and yet not sacrifice either photovoltage or excess energy loss to heat by thermalization of hot carriers.

[0009] It was shown several years ago that two-junction photovoltaic cells have the potential for achieving solar energy conversion efficiencies than single junction cells. The simplest junction device is a monolithic, two-terminal, two-junction structure, wherein the two junctions are stacked vertically.

The top junction is designed to absorb and convert the blue portion of the solar spectrum and the bottom junction absorbs and converts the red portion of the spectrum that is not absorbed by the top junction.

[0010] To achieve maximum energy conversion efficiency: 1) the junctions must be fabricated from materials that are of high electronic quality and 2) they must also be current matched, i.e. generate equal currents when exposed in the tandem configuration to the solar spectrum. The voltage generated by the cell is determined by the band gap, the amount of current generated is determined by the thickness of the layers, the quantum efficiency and other factors, e.g. light-trapping, etc. For tandem solar cells which are not exactly current matched the extra current that is generated either in the top or the bottom cell is lost.

[0011] Therefore today tandem solar cells are common in which the top cell has been thinned in order to match the currents generated by the top and bottom cell. Ordinarily, the thickness of a solar cell is chosen thick enough so that most of the light with energy higher than the band gap of the material is absorbed, yet thin enough that carriers generated toward the back of the cell can still be collected. In this way the current generated by the cell is effectively a maximum. In other words, the top cell is made thinner so that some of the light with energy above the band gap of the top cell passes through the top cell and is absorbed by the bottom cell, thus increasing the current generated by the bottom cell. In this way, the top- and bottom-cell currents are equalized, optimizing the efficiency of the tandem cell.

[0012] The currents generated in the top and bottom cells are functions not only of the band gaps of the two materials, but also of the solar spectrum and the quantum efficiency. The solar spectrum depends on the air mass, e.g. zenith angle of the sun, and various atmospheric conditions including humidity, turbidity, and cloud cover. Also, the spectrum will depend upon the geometry of collection: for cells operating under concentration only the direct beam is collected, while for flat-plate solar cells, off-normal radiation, which is rich in short wavelength light, can also be collected. Although terrestrial solar cells must operate under a range of conditions it is customary to design the solar cell for optimal efficiency under a set of conditions which will be representative of the application. Typically, solar cells are designed for operation in space under air mass 0 (AM 0) illumination, or for terrestrial operation under air mass 1.5 (AM 1.5) illumination.

[0013] In the alternative, current matching is a lesser problem when using 3 or 4-terminal devices, using either independent or parallel connection. Use of 3 and 4 terminal devices has been considered to be substantially less convenient, since the efforts for wiring and assembly increase.

[0014] U.S. Pat. No. 4,272,641 teaches that the conversion efficiency of a single junction a-Si solar cell approaches a constant when the intrinsic region thickness exceeds about 500 nm. This is due to an inherent problem with the electronic quality of a-Si. If a-Si could be made with better electronic properties then cells thicker than 500 nm would yield higher efficiencies. This problem is today circumvented in a multi-junction cell where an a-Si top-cell of less than 500nm, preferably less than 300nm is combined with a bottom cell of another type of crystallinity, e. g. of microcrystalline or crystalline type. The thickness of the bottom cell, more exactly the thickness of the absorbing intrinsic layer is then adjusted so that the current produced by said layer is about equal to the current produced by the top cell.

[0015] Today, various types of thin film solar cells based on PECVD deposited silicon are known, such as single junction type (a-Si:H) or tandem junction type, the latter being realized as a-Si:H / a-Si:H stack, a-Si / c-Si stack, a-Si / µc-Si stack. Even triple junction stacks are known. For all directly stacked tandem or triple junction designs the considerations above regarding current matching apply, because the cells are connected in series, voltages of each cell in the stack is summed, current must be same.

[0016] Today, building integrated photovoltaic (BIPV) solutions offer the opportunity to produce electrical energy by using large sun-exposed building surfaces like roofs or facades. Although normally one will try to collect in a solar cell as much as possible of an incident spectra, in some cases it is desirable to let an amount of light to pass through the photovoltaic (PV) modules so that the inner of the building is still illuminated. Typical examples are airports, train stations, sports stadiums, industrial manufacturing halls, office buildings, hotels etc.

[0017] Letting some light pass through the PV module and using some light for energy production poses at least one problem. It is not easy to let light of a pleasant color tone go though the structure: usually photovoltaic module are sensitive in a specific region of the sun spectrum. As a result, the color tone of the transmitted light may be unpleasant to people, for example red-orange light goes through amorphous Silicon thin film modules.

[0018] In some cases like in US 7,098,395; US 6,858,461 or US 5,176,758 material is locally removed from the PV module to allow passing a certain amount of light. However, the amount of energy which can be generated is reduced and additional processing steps are necessary to remove said material at the intended translucent regions. Additional processing step like etching, wet or dry, or laser-based material removal however increase cost of such PV modules considerably.

[0019] Tandem photovoltaic modules composed of an amorphous silicon (a-Si) solar cell combined with a microcrystalline Silicon (μc-Si) solar cell can improve the total efficiency of energy generation by using a larger part of the solar spectrum compared to an a-Si cell alone. The most common realization involves the deposition of a μc-Si cell on top of an a-Si cell, as e.g. illustrated in US 6,309,906.

[0020] In the context of BIPV, it is important to remember that in most cases the thermal insulation of buildings is of great importance to limit the cost of heating or cooling the inside of the building. A well known solution to reduce the thermal losses in buildings is to use double insulated glass windows.

[0021] Large area single junction PV modules can be produced cost-efficiently and omitting a back-reflector will even reduce the efforts, however the resulting panel will let only pass colored light which usually is not pleasant for the persons staying inside the buildings. Using several smaller PV active areas however increases the manufacturing complexity.

Disclosure of Invention

[0022] The invention aims at collectively resolving or amending some of the issues mentioned above: Avoid the limitations of current matching, allow a simple and easy manufacturing method for solar cells, generally suitably for BIPV, especially adequate for use as at least partially translucent solar panel.

[0023] To be more precise, the invention provides a solar device comprising at least two transparent substrates spaced apart from each other and comprising two solar cells, whereby the two solar cells are provided

- so that incident light first passes a first one of said transparent substrates then a first of the two solar cells, then the second of the two solar cells and finally the second one of said transparent substrates; and
- the two solar cells are provided spatially separated from each other and whereby the first solar cell comprises an intrinsic amorphous silicon material (a-Si).

[0024] According to a preferred embodiment of the present invention, the two transparent substrates form an insulated window.

[0025] If one considers a double insulated glass windows as known in the art: it is basically composed of two glasses a spacer and a filling gas. The two glasses can form the two transparent substrates according to the present invention.

[0026] According to a preferred embodiment of the present invention, each of the two solar cells are provided on the respective transparent substrates.

[0027] According to the invention, as illustrated below, it is proposed to deposit an electrically independent connectable a-Si cell structure (p-i-n) on one side of a first substrate, e. g. glass. The order of layers will preferably be substrate / transparent electrode / p doped Si / intrinsic a-Si / n-doped Si / transparent electrode; with the layer stack deposited on the side opposite to the incident light, as illustrated below.

[0028] According to a preferred embodiment of the present invention, second solar cell comprises an intrinsic μc-Silicon material. The term "μc" in this context is an abbreviation for microcrystalline as known to any skilled person in the field.

[0029] A μc-Si cell structure is then according to this embodiment deposited on a first surface of a the second substrate, e. g. glass, plastic etc, preferably in the order substrate / transparent electrode / n doped Si / intrinsic μc-Si / p-doped Si / transparent electrode. Reversal of the deposition sequence is possible but may lead to lower performance than when using the suggested sequence.

[0030] According to an alternative preferred embodiment of the present invention, the second solar cell comprises an intrinsic amorphous silicon material.

[0031] As an alternative to the μc-Si cell structure, a second a-Si cell structure is deposited on a first surface of the second substrate, e. g. glass, plastic etc, preferably in the order substrate / transparent electrode / n doped Si / intrinsic a-Si / p-doped Si / transparent electrode. Again, reversal of the deposition sequence is possible but may lead to lower performance than when using the suggested sequence.

[0032] In this case a so called 4 terminal tandem cell is obtained: both cells are electrically independent and exhibit four electrodes. The structuring of thin film modules is done as known in the art by patterning e. g. with laser, thus creating individual, serially interconnected cells forming a panel. These two individual panels are being joined in such a way that the coated surfaces face each other. Framing is being accomplished in a way comparable to the one of isolation windows: A spacer structure joining and keeping apart the outer peripheral regions of said preprocessed individual panels. The joining can be achieved by clamping, gluing, insert molding or alike. Electrical connecting ports can be arranged at the edges of said joined module, the bushing for the generated electrical energy can be integrated in the spacer; so decoupling of mechanical loads to the wiring can be achieved.

[0033] The a-Si cell can be produced using standard recipes as known in the industry. Since the μc-Si cell has been be produced "reversed" and the assembly was face-to-face, the order of layers as seen from incident light is substrate -> TCO -> a-Si p-i-n -> TCO -> filler gas, or filler material, -> TCO -> μc-Si p-i-n -> TCO -> substrate.

[0034] Or according to the alternative embodiment with an a-Si cell: substrate -> TCO -> a-Si p-i-n -> TCO -> filler gas, or filler material, -> TCO -> a-Si p-i-n -> TCO -> substrate.

[0035] The proposed structure has all advantages of the known tandem junction in terms of spectral exploitation, however does not include the disadvantages of the current-matching issue.

[0036] The alternative structure with two a-Si cells has the advantage of a low cost of production compared to the a-Si + μc-Si design. In this case, the tone of the transmitted light can be corrected by using color filters, e.g. red adsorbing filters or red reflecting filters so that the amount of red light is reduced giving a more pleasant tone. Therefore according to an embodiment of the present invention, the solar device comprises one or more color filters.

[0037] This solution allows choosing the amount of light that is to be absorbed in the top-cell, e.g. being closer to incident sunlight than the bottom cell, by adapting the thickness individually, e. g. reducing the thickness of each cell. Because the cells are not electrically connected it is not necessary to match the current from one cell with the current of the other cell, thus increasing the flexibility in choosing thickness etc.

[0038] According to a preferred embodiment of the present invention, the thickness of the intrinsic amorphous silicon layer of the first solar cell is ≤ 300 nm, preferably ≤ 250 nm, more preferred ≤ 200 nm and most preferred ≤ 150 nm.

[0039] According to a preferred embodiment of the present invention, the second solar cell comprises an intrinsic amorphous silicon material and the thickness of the intrinsic amorphous silicon layer of the second solar cell is ≤ 300 nm, preferably ≤ 250 nm, more preferred ≤ 200 nm and most preferred ≤ 150 nm.

[0040] According to an alternative preferred embodiment of the present invention, the second solar cell comprises a μc-Silicon silicon material and the thickness of the intrinsic μc-Silicon layer of the second solar cell is ≤ 300 nm, preferably ≤ 250 nm, more preferred ≤ 200 nm and most preferred ≤ 150 nm.

[0041] The aforementioned components, as well as the claimed components and the components to be used in accordance with the invention in the described embodiments, are not subject to any special exceptions with respect to their size, shape, material selection and technical concept such that the selection criteria known in the pertinent field can be applied without limitations.

[0042] Additional details, characteristics and advantages of the object of the invention are disclosed in the subclaims and the following description of the respective figures--which in an exemplary fashion--show one preferred embodiment of a solar device to the invention.

Brief Description of Drawings

[0043] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

[0044] Fig. 1 shows a very schematic embodiment of a solar device of the present invention; and

[0045] Fig. 2 shows a diagramm of the transmission of a µc-Silicon solar cell with a thickness of the intrinsic layer of 300nm for use in a solar device of the present invention.

Detailed Description of the Embodiments

[0046] Fig. 1 shows a very schematic embodiment of a solar device 1 of the present invention. This device comprises two transparent substrates 10 and 20 which can be made of glass or plastic or other suitable materials known in the field. It should be noted that in Fig 1 the solar device is provided so that the "outside", e.g. of a building etc, is on the side of the substrate 10, whereas the "inside" is on the side of substrate 20.

[0047] The two transparent substrates 10, 20 form an insulated window. For this use, two adjuvant stacks 50, 51 are provided. It should be noted that Fig. 1 is highly schematic and that in reality the dimensions will be quite different. The two stacks 50, 51 can be made of any material or be of any form known in the field. The insulated window formed by the two substrates 10, 20 and the stacks 50, 51 is filled with an insulating gas 60.

[0048] Provided on the first transparent substrate 10 is a first solar cell 30, which comprises an a-Si cell structure. Most preferred the a-Si cell structure will have a (p-i-n) order, more precisely the order of layers is: substrate / transparent electrode / p doped Si / intrinsic a-Si / n-doped Si / transparent electrode. As can be seen, the solar cell is deposited with the layer stack on the side opposite to the incident light, which will come from the "outside", i.e. from the "top" of Fig. 1.

[0049] Provided on the second transparent substrate 20 is a second solar cell 40 which is spatially remote from said first solar cell 30. Because the cells are remote from each other and not electrically connected it is not necessary to match the current from one cell with the current of the other cell, thus increasing the flexibility in choosing thickness etc.

[0050] The second solar cell 40 can preferably either be a µc-Si cell or an a-Si-cell.

[0051] In the first case the order of layers as seen from incident light is substrate, and including the first solar cell 30, is preferably: -> TCO -> a-Si p-i-n -> TCO -> filler gas, or filler material, -> TCO -> µc-Si p-i-n -> TCO -> substrate.

[0052] In the latter case it is: substrate -> TCO -> a-Si p-i-n -> TCO -> filler gas, or filler material, -> TCO -> a-Si p-i-n -> TCO -> substrate.

[0053] Fig. 2 shows a diagram of the transmission of a µc-Silicon solar cell with a thickness of the intrinsic layer of 300 nm for use in a solar device of the present invention, or to put it otherwise an example of the expected transmission from a single junction a-Si cell with reduced thickness. The thick black line show the measured transmitted light in the visible range, approximately 400 nm to 800 nm, in a standard a-Si cell without back reflector.

[0054] The transmission curve was measured on a standard a-Si cell of approx. 300 nm thickness. If the thickness of the cell i-layer is reduced to 1/3, 1/2 or 2/3 of the original thickness, a clear increase of the amount of transmitted light is to be expected.

[0055] Light transmitted through the a-Si module will be partly absorbed in the microcrystalline module and partly transmitted. Again, tuning of the thickness of the microcrystalline module can be used to tune the amount of transmitted light.

[0056] The total amount of light transmitted through the complete stack will be lower than depicted in figure 2.

[0057] The color tone of the transmitted light can be optimized by modifying the relative thickness of the two cells.

[0058] If necessary an additional color filter can be added to the structure to improve the color tone.

[0059] It is further possible to combine the inventive solution with the a. m. Prior Art, e. g. areal patterning of the individual patterns. One or both panels can be patterned, even with individual designs, so that regular or irregular designs or patterns can be achieved.

[0060] The voltage produced by each sub-module can be chosen independently of the voltage of the other sub-module by changing the number of segments connected in series. If the two sub-modules are not connected together, a four terminal device is obtained. However, by carefully setting the voltages of both sub-modules so that they are similar, it is possible to connect both sub-modules in parallel thus obtaining a normal two terminal device. By using a parallel connection, the voltage generated by each sub-module should be similar and the total current produced will be the sum of the currents generated in each sub-module. In the case of a-Si and μc-Si sub-modules, the μc-Si sub-module should have approx. the double number of segments than the a-Si sub-modules.

[0061] The filling gas of double-insulated glass windows has the function of a protective gas and therefore allows omitting the production step of laminating the modules with plastic foils, e.g. PVB, PVA, or alike. The gas must be without oxygen and without water in order to guarantee durability of said semiconductor/TCO stacks.

[0062] Additionally, it is possible to add Oxygen and water gettering materials to the window frame.

[0063] The particular combinations of elements and features in the above detailed embodiments are exemplary only; the interchanging and substitution of these teachings with other teachings in this and the patents/applications incorporated by reference are also expressly contemplated. As those skilled in the art will recognize, variations, modifications, and other implementations of what is described herein can occur to those of ordinary skill in the art without departing from the spirit and the scope of the invention as claimed. Accordingly, the foregoing description is by way of example only and is not intended as limiting. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measured cannot be used to advantage. The invention's scope is defined in the following claims and the equivalents thereto. Furthermore, reference signs used in the description and claims do not limit the scope of the invention as claimed.

Claims

1. Solar device (1) comprising at least two transparent substrates (10, 20) spaced apart from each other and comprising two solar cells (30, 40), whereby the two solar cells (30, 40) are provided
   - so that incident light first passes a first one of said transparent substrates (10) then a first of the two solar cells (30), then the second of the two solar cells (40) and finally the second one of said transparent substrates (20); and
   - the two solar cells (30,40) are provided spatially separated from each other and whereby the first solar cell (30) comprises an intrinsic amorphous silicon material.
2. Solar device according to claim 1 whereby the two transparent substrates (10, 20) form an insulated window.
3. Solar device according to claim 1, whereby each of the two solar cells (30, 40) are provided on the respective transparent substrates (10, 20).
4. Solar device according to claim 1, whereby the second solar cell (40) comprises an intrinsic µc-Silicon material.
5. Solar device according to claim 1, whereby the second solar cell (40) comprises an intrinsic amorphous silicon material.
6. Solar device according to claim 1, whereby the thickness of the intrinsic amorphous silicon layer of the first solar cell (30) is ≤ 300 nm
7. Solar device according to claim 1, whereby the second solar cell (40) comprises an intrinsic amorphous silicon material and the thickness of the intrinsic amorphous silicon layer of the second solar cell (40) is ≤ 300 nm.
8. Solar device according to claim 1, whereby the second solar cell (40) comprises an intrinsic µc-Silicon silicon material and the thickness of the intrinsic
   µc-Silicon layer of the second solar cell (40) is ≤ 300 nm.
9. Solar device according to claim 1, furthermore comprising one or more color filters.

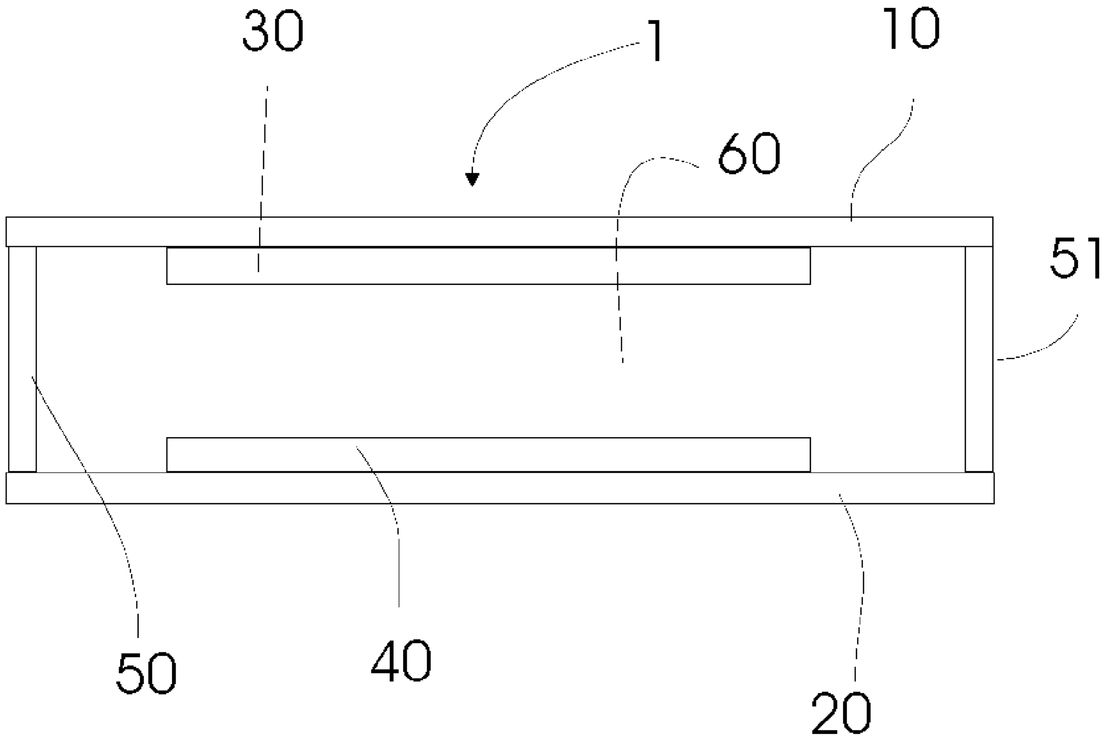
30
1
10
60
51
50
40
20

Fig. 1

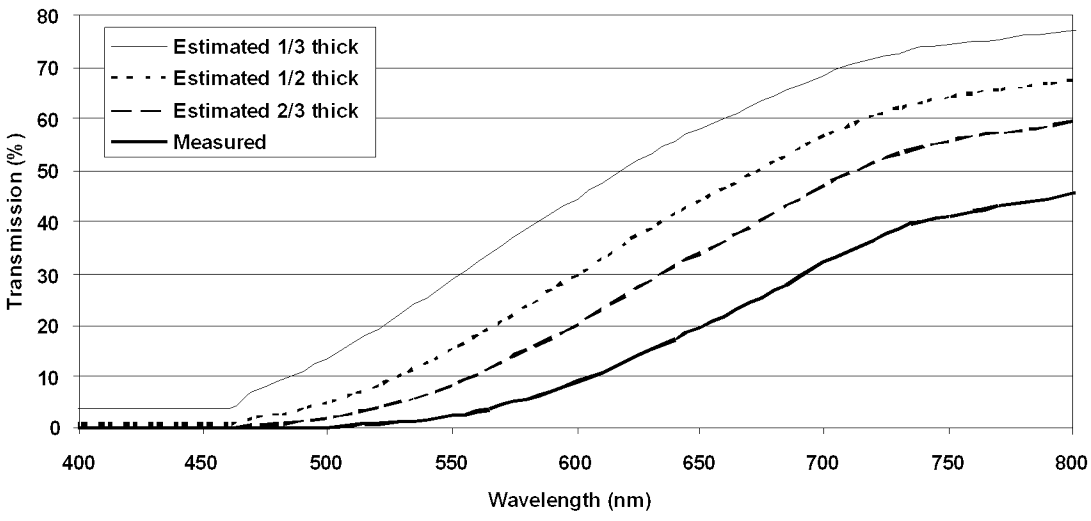
Estimated 1/3 thick
Estimated 1/2 thick
Estimated 2/3 thick
Measured
Transmission (%)
Wavelength (nm)
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
800

Fig. 2