FIG. **5** is a graphical illustration of the measured current density under 1× sun and 10× sun of one embodiment of the IBSC shown in FIG. **4**, in accordance with one or more embodiments of the present disclosure.

FIG. **6** is a graphical illustration of the measured External Quantum Efficiency (EQE) reading of one embodiment the IBSC shown in FIG. **4**, in accordance with one or more embodiments of the present disclosure

FIG. **7**A is a block diagram representation of an intermediate band solar cell (IBSC) with p-type absorber layer in accordance with one or more embodiments of the present disclosure.

FIG. **7**B is a graphical illustration of a calculated band diagram for one embodiment of the IBSC shown in FIG. **7**A, in accordance with one or more embodiments of the present disclosure.

FIG. **8**A is a block diagram representation of an intermediate band solar cell having graded compositions (graded IBSC) in accordance with one or more embodiments of the present disclosure.

FIG. **8**B is a graphical illustration of a calculated band diagram for one embodiment of the graded-IBSC shown in FIG. **8**A, in accordance with one or more embodiments of the present disclosure.

DETAILED DESCRIPTION

In general, the present disclosure is directed to a photovoltaic device, solar cell or intermediate band solar cell (IBSC) having improved solar power conversion efficiency through the use of a single semiconductor with multiple band gaps. In a semiconductor including such an intermediate band, an additional one or more bands in the band gap of a wide gap semiconductor serve as "stepping stones" to transfer electrons from the valence to the conduction band with two or more photons of energy smaller than the band gap. This IBSC concept requires only a single p/n junction but the intermediate bands have to be electrically isolated from charge collecting contacts. Theoretical modeling predicts power conversion efficiency of 63% for a device with one and 72% for a device with two intermediate bands.

More particularly, the present disclosure is directed to dilute Group III-V nitride intermediate band solar cells (IBSCs) having contact blocking layers providing improved solar cell performance. The substitution of small amount of nitrogen in a III-V semiconductor alloy (such as GaAs, InGaAs, or GaAsP) splits the conduction band of the alloy into a higher conduction band (E_C) and a lower subband, or the intermediate band (IBand). By utilizing a photovoltaic device, solar cell or IBSC including dilute Group III-V nitride layers and also contact blocking layers, the IBSC of the present disclosure is able to maximize solar cell performance, increase voltage and current within an IBSC and also prevent electrons and holes from escaping the layers through conduction in the IBand of an IBSC. Certain embodiments of the present disclosure will now be discussed with reference to the aforementioned figures, wherein like reference numerals refer to like components.

By utilizing an IBSC, a single P-N junction may be employed, thereby lowering production costs by considerably simplifying the solar cell design over more complex multijunction solar cells. Further, the IBSC will achieve greater power conversion efficiencies over conventional single P-N junction solar cells by fabricating the IBSC using materials that optimize three or more energy bands in order. Conventionally, finding a multiband semiconductor absorber layer and electrically isolating the IBand in the absorber layer has been a challenge. IBSC test devices using InAs quantum dots (QD) miniband concept and dilute III-V nitride result in low open circuit voltage (V_{OC}) readings, e.g. 0.3-0.4 eV. These lower V_{OC} readings occurred for conventional IBSCs either because of non-ideal band separation (as in the InAs QD concept) or because electrons and holes continuously leave the layers of an IBSC through conduction in the IBand due to the lack of electrical isolation of the IBand in the absorber layer in the IBSC with the neighboring layers. The present inventors have solved these electrical isolation issues surrounding IBSCs using the concept of band anti-crossing in highly mismatched alloys (HMAs) which enables the usage of II-VI and III-V semiconductor alloys that have a multiband structure appropriate for IBSC applications.

Referring now to FIG. **1**, a block diagram illustration of an intermediate band solar cell (IBSC) **100** is shown generally in accordance with one or more embodiments of the present disclosure. IBSC **100** includes a bottom substrate layer **102** formed of any substrate material commonly used in solar cells. For example, substrate layer **102** may comprise Germanium (Ge) or Gallium Arsenide (GaAs) and substrate layer **102** may comprise an n-type or p-type material as desired for a particular application.

IBSC **100** includes two layers **106** and **108** of dilute III-V nitride materials that comprise a single P-N junction for IBSC **100** having multiple energy bands, wherein n-type material is formed on one side of the P-N junction and p-type material is formed on the other side of the P-N junction. In one or more embodiments, P-N junction layers **106** and **108** comprise respective layers of GaNAs. In the particular embodiment illustrated in FIG. **1**, layer **106** is formed as n-GaNAs and layer **108** is formed as p-GaNAs, while it is understood that the order of these p-type and n-type layers could be reversed for different applications (e.g., see FIG. **8**). GaNAs P-N junction layers **106** and **108** may also be referred to herein as GaNAs absorber layers **106** and **108**. In one or more embodiments, the nitrogen concentration within the GaNAs absorber layers **106** and **108** ranges from 0.5-5%. Other III-V nitrides that have similar multiband properties as GaNAs can also be used as IBand absorbers, such as but not limited to AlGaNAs and GaNAsP.

In one or more embodiments, Indium (In) may be added to at least one of the layers **106** and **108** so as to form a GaInNAs layer **106** or GaInNAs layer **108** in order to improve the lattice-matching parameters of the material, which improves the overall quality of the material and reduces material-based defects that could occur from routine usage and testing that could otherwise harm the efficiency of the IBSC **100**. In one or more embodiments, the proportion of Nitrogen (N) to Indium (In) in layers **106** and **108** is selected to have a 1:3 ratio, in order to yield optimal results and to compensate for the Nitrogen-induced contraction of the lattice parameter caused by the presence of Nitrogen in a compound.

In one or more embodiments, a pair of contact blocking layers **104** and **110** are positioned on opposite surfaces of the P-N junction in IBSC **100**, such that a first contact blocking layer **104** is formed on substrate layer **102** adjacent to n-GaNAs layer **106** and a second contact blocking layer **110** is formed on p-GaNAs layer **108**. While a pair of contact blocking layers **104** and **110** are illustrated in FIG. **1**, it is further understood that IBSC **100** may be formed in some embodiments with only one of the contact blocking layers **104** and **110** formed adjacent to the n-type of the layers **106** and **108**. Thus, at least one contact blocking layer (i.e., **104** or **110**) is formed adjacent to the n-type of the layers **106** and **108**, while in some embodiments another contact blocking layer (i.e., **104** or **110**) may further be formed adjacent to the p-type of