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Ultrahigh efficiencies in vertical epitaxial heterostructure architectures

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Optical to electrical power converting semiconductor devices were achieved with breakthrough performance by designing a Vertical Epitaxial Heterostructure Architecture. The devices are featuring modeled and measured conversion efficiencies greater than 65%. The ultrahigh conversion efficiencies were obtained by monolithically integrating several thin GaAs photovoltaic junctions tailored with submicron absorption thicknesses and grown in a single crystal by epitaxy. The heterostructures that were engineered with a number N of such ultrathin junctions yielded an optimal external quantum efficiencies approaching 100%/N. The heterostructures are capable of output voltages that are multiple times larger than the corresponding photovoltage of the input light. The individual nanoscale junctions are each generating up to ~1.2 V of output voltage when illuminated in the infrared. We compare the optoelectronic properties of phototransducers prepared with designs having 5 to 12 junctions and that are exhibiting voltage outputs between >5 V and >14 V. © 2016 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4941240]

Thin nanoscale p/n junctions have recently been a stimulated field of research for reducing the cost and/or increasing the performance of solar cells,1–5 for applications in phototransducer optoelectronic devices with high conversion efficiencies,6–10 for microelectronic hybrid components,11 or for biomedical applications.12 All these applications are hankering for a reduction of the residual losses while transforming an optical power source into a usable supply of electrical power. In the above fields, it is also typically advantageous to convert the photons directly into an operational output voltage in the 5 V to 12 V range. These features are sought after in order to enable more compact, electrically isolated, or long-lasting power sources. Such isolated power supplies are beneficial for regulating more securely microelectronic circuits in many telecommunication, utilities, sensor, and automotive systems, or for controlling more safely neuro-stimulating or biomedical devices. However, the thin semiconductor junctions typically do not absorb all the input photons due to the restricted semiconductor cross-section available. Nevertheless, photon confinement architectures1–8 or vertical arrangements have been designed to exploit the unique photocarrier properties of such sub-micron thin films. These strategies have been used effectively in some cases to circumvent the reduction in short-circuit current (Isc) which is otherwise unavoidable.11,12

Consequently, this area of research can benefit from a systematic investigation of the photocarrier properties in state-of-the-art photovoltaic devices exploiting such nanoscale III-V semiconductor heterostructures. In this work, we perform a systematic study of the properties of thin GaAs p/n junctions with different thicknesses and then, based on these results, we demonstrate the implementation of a unique Vertical Epitaxial Heterostructure Architecture (“VEHSA” design) with up to 12 photovoltaic junctions having p-bases as thin as 44 nm. To obtain an accurate evaluation of the photon absorption and of the photocarrier extraction in the VEHSA devices, we performed a detailed investigation of thin GaAs p on n/p photovoltaic heterostructures prepared with a full range of thicknesses. The n-type emitter is here kept at ~100 nm or thinner, and the p-type base layer is varied in thickness.17 The total n/p absorbing thickness is systematically varied from partially absorbing (p-base of 112 nm) to quasi-fully absorbing (p-base greater than 2.5 μm). The variations in the optical properties with base layer thickness are well explained with a model based on a 2D axis-symmetric model TCAD (Technology Computer-Aided Design) implementation of the heterostructures. The measured and modeled properties of the different heterostructures provide valuable insight for the precise determination of the spectral dependence of the absorption and the photocarrier properties in optoelectronic devices leveraging such thin GaAs n/p junctions. The thickness dependence of the spectral response obtained from the external quantum efficiency (EQE) and from the photocurrent has been measured at 25°C and is shown in Figs. 1 and 2, respectively. The heterostructures have been grown by metal-organic chemical vapor deposition (MOCVD) on 150 mm diameter (100) Zn-doped p-type GaAs substrates with an Aixtron 2600 multi-wafer reactor using optimal GaAs growth conditions. The particulars of device growth and the fabrication have been described previously.11

The n/p GaAs junctions are grown within lattice-matched GaInP layers forming a p-type back surface field and an n-type window layer, below and above the n/p GaAs, respectively. We also use the high peak current tunnel junctions described previously11 for all the structures except for the PT5 devices which are limited in the present study to

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The properties measured from the various heterostructures are also used to build a predictive model. The simulation is based on a 2D, axis-symmetric model TCAD implementation of the heterostructures. We adopt material parameter values for GaAs and GaInP that are achievable in state-of-the-art materials. An approximate treatment of photon recycling effects is included by rescaling B to $B(1 - \gamma)$ with a photon recycling factor of $\gamma$ with different values between 0 and 1 for the various junctions of the stack.

The measured EQE values obtained at a particular wavelength from the individual $n/p$ junction of Fig. 1 allow extracting the associated absorption coefficients. It can then be used to provide accurate information for designing VEHSA devices with a varied number of even thinner $n/p$ junctions. The corresponding results are shown for an input at 830 nm in Fig. 2. The EQE data are also in good agreement with the measured $I_{sc}$ values. The data fit well the expected photocurrent dependence on junction thickness, as modeled with $I_{sc} = Io[1 - \exp(-\alpha t)]$. The absorption coefficient $\alpha$ of the probe beam can be determined with good accuracy using this method, based on the nominal values of the $n/p$ junction thickness (t). The methodology is equivalently applied to the EQE data with comparable accuracy for the wavelengths of interest.

The lower EQE is obtained with devices stacking 5 $n/p$ junctions arranged in the Vertical Epitaxial Heterostructure Architecture (VEHSA design). The lower EQE is obtained with devices stacking 5 $n/p$ junctions arranged in the Vertical Epitaxial Heterostructure Architecture (VEHSA design).
The PTN VEHSA heterostructures incorporating $N$ such $n/p$ structures are then modeled to evaluate the current-voltage (I-V) characteristics of the stacked structures. The power dependence of the modeled and measured output voltage and conversion efficiency for the PT5, PT6, PT8, and PT12 heterostructures is shown in Figs. 4 and 5, respectively. The experimental results are comparing favorably with the modeled values. While multi-junction concentrated photovoltaic solar cells have demonstrated impressive record efficiencies at 46%, the modeled values. While multi-junction concentrated photovoltaic solar cells have demonstrated impressive record efficiencies at 46%, the measured efficiencies tend to decrease faster with increasing optical input powers than expected from the model. It suggests that this simulation is likely an upper bound, and that lower values are more characteristic here. At higher input powers, the voltage decreases slightly due to the heating of the devices from the unconverted optical power.

The results demonstrate a remarkable 3 W of electrical output power converted at 14.5 V with Eff $>$ 50%. However, as demonstrated in Fig. 5, measured Eff $\sim$ 70% $\pm$ 5% has been observed with the PT5 devices when the input wavelength is tuned to the nominal wavelength of the VEHSA design. These efficiencies are slightly higher than the one previously reported due mainly to a better wavelength tuning. The efficiencies are measured using a high-power laser diode at a fixed wavelength. The optical input power is determined by measuring with a power meter the laser output power with an accuracy better than $\sim$2%. The electrical output power is obtained from the measured I-V curves at the maximum power point. The stacked architecture also favors enhanced electrical power extraction because of the resulting operation at higher voltages but lower currents. The latter reduces the impact of the resistive losses during the photocarrier extraction process. Furthermore, it can be observed in Fig. 4 that the measured output voltage matches better the modeled values when no bandgap narrowing (BN) effects are included in the model for the $n$-GaAs. This suggests that the $\sim$0.1 eV BN previously reported is likely an upper bound, and that lower values are more characteristic here. At higher input powers, the voltage decreases slightly due to the heating of the devices from the unconverted optical power.

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16See supplementary material at http://dx.doi.org/10.1063/1.4941240 for model and structure details.


