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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 \( \sim 1.2 \text{ V} \) 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 \( > 5 \text{ V} \) and \( > 14 \text{ V} \).

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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,1–9 for applications in phototransducer optoelectronic devices with high conversion efficiencies,10–14 for microelectronic hybrid components,15 or for biomedical applications.16 All these applications are hampering 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 (\( I_{sc} \)) which is otherwise unavoidable.11,12

Consequently, this area of research can benefit from a systematic investigation of the photocarrier properties in optoelectronic 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 \( n \) on \( p \) (\( n/p \)) photovoltaic heterostructures prepared with a full range of thicknesses. The \( n \)-type emitter is here kept at \( \sim 100 \text{ nm} \) or thinner, and the \( p \)-type base layer is varied in thickness.17 The \( n/p \) absorbing thickness is systematically varied from partially absorbing (\( p \)-base of 112 nm) to quasi-fully absorbing (\( p \)-base greater than 2.5 \( \mu \text{m} \)). The variations in the optical properties with base layer thickness are well explained with a model (Silvaco) 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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define the features of the top silver metal grid pattern of the devices engineered with the VEHSA design with 5
junctions: structure S1 is 2536 nm, S2 is 481 nm, S3 is 246 nm, S4 is 146 nm, and S5 is 112 nm thick. These thick-
esses were chosen for current-matching in phototransducer heterostructures having various thicknesses. The data are from the statistics of many devices using a modified commercial solar cell wafer tester. The Isc and EQE obtained at 830 nm (crosses) are measured at 25°C with this vertical arrangement are yielding an optimal external EQE of close to 100%/5 at the designed wavelength of 830 nm. The architecture of the PT6, PT8, and PT12 VEHSA structures can then be designed with correspondingly thinner n/p junctions. The EQE data are shown for all these heterostructures in Fig. 3. Clearly the current is matched in all the junctions at the design wavelength and it results in an EQE approaching 100%/N at the peak, here between 805 nm and 845 nm (depending on the different designs for applications in that range). Remarkably, the thickness of the narrowest p-bases is only 44 nm thick for the PT12 heterostructure.

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 − γ) with a photon recycling factor of γ with different values between 0 and 1 for the various junctions of the stack.

The lower EQE is obtained with devices stacking 5 n/p junctions arranged in the Vertical Epitaxial Heterostructure Architecture (VEHSA design).

FIG. 1. Spectral response of thin photovoltaic devices with various base thicknesses and with the corresponding PTS VEHSA heterostructure. The EQE is shown for the different structures, as indicated in the legend. The lower EQE is obtained with devices stacking 5 n/p junctions arranged in the Vertical Epitaxial Heterostructure Architecture (VEHSA design).

FIG. 2. Measured photocurrent (Isc) and quantum efficiency. The Isc (circles) and EQE data are fitted by modeling with $I_{sc} = I_{sc}[1 - \exp(-at)]$ and $EQE = EQE,[1 - \exp(-at)]$, solid/dashed lines, where a is the absorption coefficient of the probe beam and t is the thickness of the n/p junction. The illumination intensity for the I-V curves is ~8 W/cm²; the active device area is 0.034 cm².

FIG. 3. Spectral response of the GaAs-based PTN phototransducer heterostructures engineered with the PTN VEHSA design. The external quantum efficiency (EQE) data measured at 25°C are shown for $N = 5, 6, 8, 12$ junctions. The current is matched in all the various junctions at the design wavelength, between 805 nm and 845 nm, resulting in an EQE approaching 100%/N at that nominal wavelength.
Unless indicated, bandgap narrowing effects are included in accordance with previously reported \( n\)-GaAs\(^{20,21}\) and \( p\)-GaAs\(^{22}\). These parameters yield modeled open circuit voltages within a small margin to those measured. The band alignment for the GaAs–GaInP heterojunctions was specified manually so that intrinsic samples would exhibit a 0.2 eV discontinuity in the conduction bands.\(^{24}\) The incident flux is modeled via a uniform monochromatic 830 nm beam of radius 1.033 mm, yielding an external EQE of 91% when the individual \( p\)-GaAs base layer thickness is 2536 nm. The model therefore allows to predict the I-V characteristics of the individual thin junctions, to study how the carrier dynamics is modified in such ultra-thin devices, and to explore what are the thickness limits.\(^{25}\)

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%,\(^{36}\) here the modeled and measured values are matching better the modeled values when no bandgap narrowing (BN) effects are included in the model for the \( n\)-GaAs.\(^{21}\) This suggests that the ~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.

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 ~ 70% ± 5% has been observed with the PT5 devices when the input wavelength is tuned to the peak response the efficiency approaches 70%. No Bragg reflector or back side mirror is used.

FIG. 4. Measured and modeled output voltage. GaAs-based heterostructures engineered with the VEHSA design. The open circuit voltage (\( V_{oc} \)) is shown as a function of the electrical output power for devices incorporating \( N = 5, 6, 8, \) and 12 \( n/p \) junctions. The active area is 0.034 cm\(^2\) with gridlines as reported previously.\(^{23}\) The temperature is set to 25 °C. The model with no bandgap narrowing ("no BN") predicts higher \( V_{oc} \) values that match closely the measured values.
reduction of device thicknesses. This has allowed us to predict the performance of devices with different absorption thicknesses and to assess the potential for improvement. We have also demonstrated that the PTN heterostructure designs yielded an optimal QE approaching 100%/N in the spectral range around the design wavelength. We have shown that the best properties of such ultra-thin n/p junctions can be directly exploited in optoelectronic devices based on a VEHSA design. Our device model shows that unprecedented 70% conversion efficiencies are achievable with Voc exceeding 14 V and with a few watts of electrical output powers. The high efficiencies were measured on the PT5 devices and using 14 V and with a few watts of electrical output powers. We can also deduce that the voltage of the thinner n/p junction can be higher than for the thicker heterostructures by at least ~20 mV.

Our systematic investigation of the photocarrier properties of devices with different absorption thicknesses allowed us to study and to effectively implement partially absorbing junctions having a p-doped base as thin as 44 nm. We demonstrated that the PTN heterostructure designs yielded an optimal QE approaching 100%/N in the spectral range around the design wavelength. We have shown that the interesting properties of such ultra-thin n/p junctions can be directly exploited in optoelectronic devices based on a VEHSA design. Our device model shows that unprecedented 70% conversion efficiencies are achievable with Voc exceeding 14 V and with a few watts of electrical output powers. The high efficiencies were measured on the PT5 devices and further studies are dedicated at measuring such high efficiencies for tuned conditions with the PT12 devices.

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