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Lattice-Matched GaNPAs-on-Silicon Tandem Solar Cells

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LATTICE-MATCHED GaNPAs-ON-SILICON TANDEM SOLAR CELLS

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ABSTRACTS

A two-junction device consisting of a 1.7-eV GaNPAs junction on a 1.1-eV silicon junction has the theoretical potential to achieve nearly optimal efficiency for a two-junction tandem cell. We have demonstrated a monolithic III-V-on-silicon tandem solar cell in which most of the III-V layers are nearly lattice-matched to the silicon substrate. The cell includes a 1.8 eV GaNPAs top cell, a GaP-based tunnel junction (TJ), and a diffused silicon junction formed during the epitaxial growth of GaNP on the silicon substrate. This tandem on silicon has a V_{oc} of 1.53 V and an AM1.5G efficiency of 5.2% without any antireflection coating. Low currents in the top cell are the primary limitation to higher efficiency at this point.

INTRODUCTION

III-V semiconductors grown on silicon substrates are very attractive for lower-cost, high-efficiency multijunction solar cells. A two-junction device consisting of a 1.7–eV junction on a 1.1–eV silicon junction has the theoretical potential to achieve nearly optimal efficiency for a two-junction cell [1]. Most of the previous work on such a structure focused on III-V top cells that were lattice-mismatched to the silicon bottom cell. Under the best conditions, this leads to a threading dislocation density on the order of 10^6 cm^{-2} in the III-V top cell [2]. This dislocation density decreases the electronic quality of the top cell [3] to the point that a lattice-matched tandem solar cell with a less optimal band-gap combination (e.g. GaInP/GaAs) is much more efficient [4].

$GaN_xP_{1-x-y}As_y$, hereafter GaNPAs, is a direct-gap [5] III-V alloy that can be grown lattice-matched to Si with very low structural defect densities [6]. We have proposed the use of lattice-matched GaNPAs on silicon for high-efficiency multijunction solar cells [7]. Such a cell would have application in space power systems, as well as terrestrial concentrators. In this paper, we present results on the first lattice-matched GaNPAs-on-silicon tandem solar cells.

TANDEM SOLAR CELL DESIGN

We have fabricated the monolithic III-V-on-silicon tandem solar cell shown schematically in Fig. 1. The cell is functionally comprised of an n-on-p silicon bottom homojunction, a III-V tunnel junction, and a 1.8 eV n-i-p GaNPAs top junction. The epitaxial portions of the structure are composed mainly of GaNPAs and GaNP layers that are lattice-matched to the single-crystal silicon substrate. A few thin layers were composed of lattice-mismatched GaP or GaAs for reasons to be discussed below.

Epitaxial III-V layers were grown on single-crystal Czochralski silicon substrates by atmospheric-pressure metal-organic chemical vapor phase epitaxy (MOVPE) using triethylgallium, phosphine (PH_3), t-butylarsine, and dimethylhydrazine (DMH) sources. Prior to growth, the silicon substrates were cleaned in an ammonia / hydrogen peroxide solution, rinsed in deionized water, and spun dry. The native silicon oxide was removed *in situ* by annealing at 1000°C under H_2. A thin (<40 nm) GaP nucleation layer was grown under a high partial pressure of PH_3 (~10 torr) while reducing the temperature to 800°C at 100°C/min. A 0.5 μm thick $GaN_{0.02}P_{0.98}$ buffer layer was then grown at 700°C at 1 μm/h.

By varying the lattice-matched composition of $GaN_xP_{1-x-y}As_y$, direct bandgaps in the range of 1.5 to 2.0 eV can be achieved [7]. Nearly lattice-matched $GaN_{0.04}P_{0.86}As_{0.1}$ layers with a bandgap of about 1.80 eV were used as the absorber layer in the top junction here.

The GaP nucleation layer was grown without nitrogen because the DMH appears to react with the silicon surface

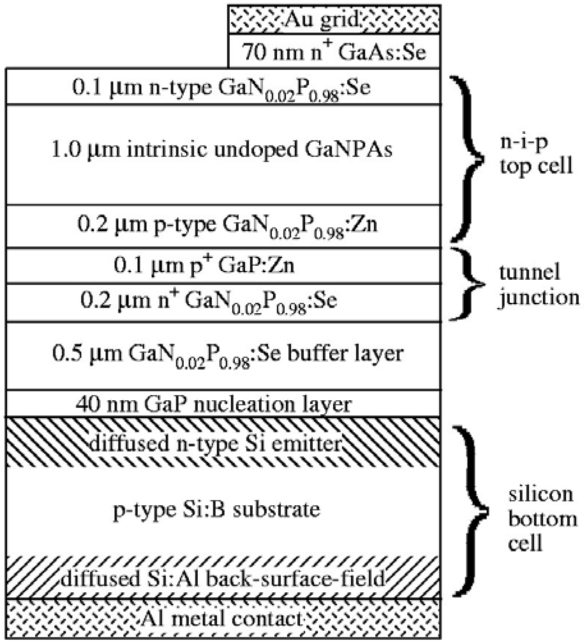

Fig. 1: Schematic of GaNPAs-on-silicon tandem solar cell

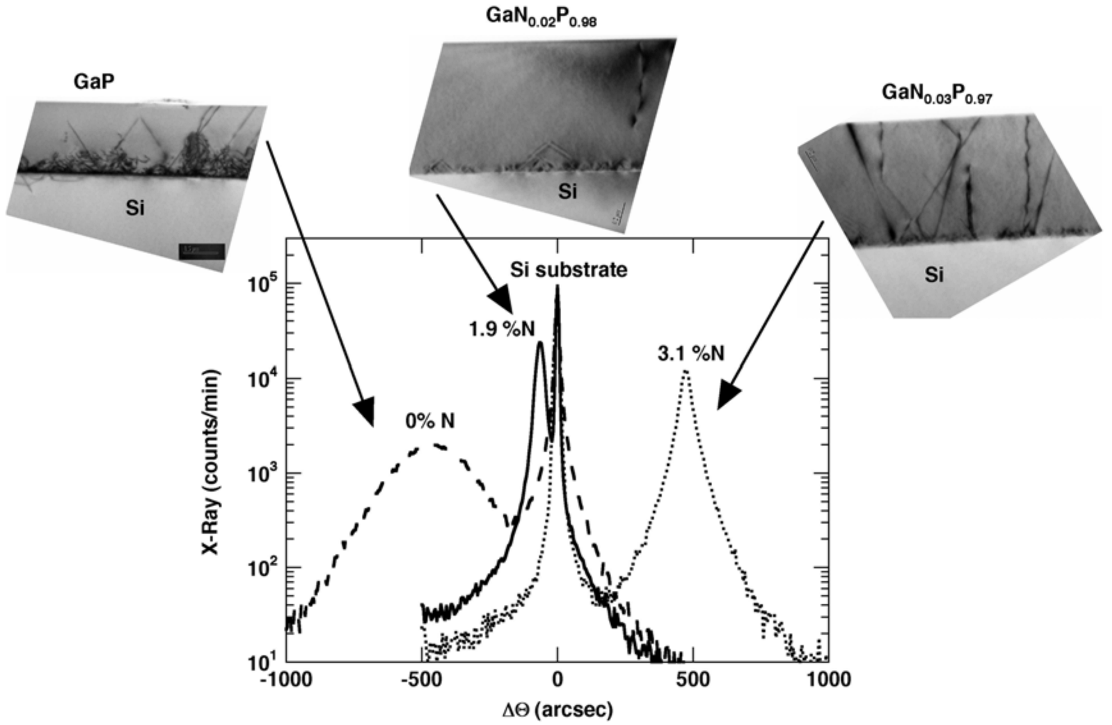

Fig. 2: X-ray diffraction of GaN_xP_{1-x} grown on silicon taken in (004) reflection with corresponding TEM images.

creating undesired silicon nitride regions which disrupt the epitaxial nature of the growth. A thickness of 40 nm of GaP on silicon is below the critical thickness.

Using this nucleation scheme [8], high crystalline quality was achieved only when the thicker GaNP layer was closely lattice-matched to the silicon. Fig. 2 shows transmission electron microscope (TEM) images and X-ray diffraction results of various compositions of GaNP layers. The lattice-matched $GaN_{0.02}P_{0.98}$ layer shows low defect density away from the interface and X-ray peak widths as low as 24 arcsec. In spite of an imperfect nucleation scheme, the defects apparent at the GaP/Si interface appear not to propagate into the epilayer during the growth of the lattice-matched composition.

The electrical quality of GaNP(As) is highly dependent on growth conditions. In particular, growth conditions that minimize unintentional carbon and hydrogen contamination provide the highest carrier lifetimes [9]. Thus, the GaNPAs top junction was grown at 700°C and a growth rate of 1 μm/h. Similar to the case of most GaInNAs material [10], GaNPAs grown to-date appears to have very short diffusion lengths, even when special care is taken to minimize H and C contamination. Fig. 3 shows how the spectral response of $GaN_{0.02}P_{0.98}$ grown on silicon increases dramatically with the depletion width. Thus, an n-i-p device employing field-aided collection was used to maximize QE. Unlike MOCVD-grown GaInNAs material, intrinsic GaNPAs has relatively low carrier concentrations so that high QEs can be achieved in an n-i-p structure.

During the epitaxial growth of GaNPAs on silicon at 700°C, significant diffusion of the III-V atoms into the silicon occurs. When a 0.5-μm $GaN_{0.02}P_{0.98}$ layer is grown on a p-type, B-doped silicon (1-10 Ω-cm) substrate, an n-p homojunction is created in the silicon. But when the same layer is grown on an n-type, P-doped silicon (1-10 Ω-cm) substrate, no silicon homojunction is created. This is because a greater concentration of P than Ga diffuses into the silicon from the III-V epilayers. The diffused junction formed in the p-type silicon during growth of the GaNP layer was analyzed after selectively etching the III-V layers from the silicon using a 3 HCl : 1 HNO_3 solution. Fig. 4 shows the P concentration profile as measured by

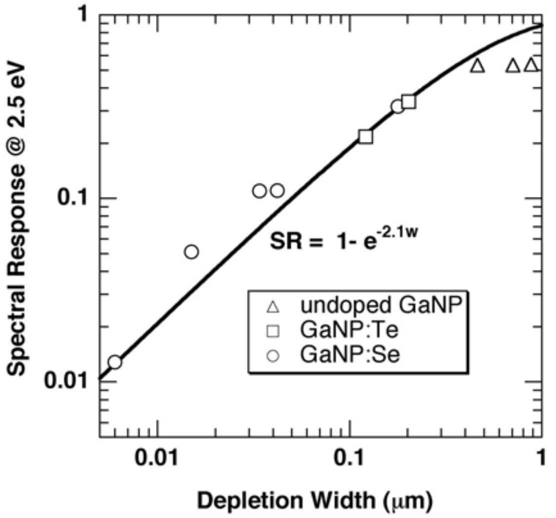

Fig. 3: Spectral response of $GaN_{0.02}P_{0.98}$ grown on silicon for a variety of n-type doping levels. The fit implies short diffusion lengths.

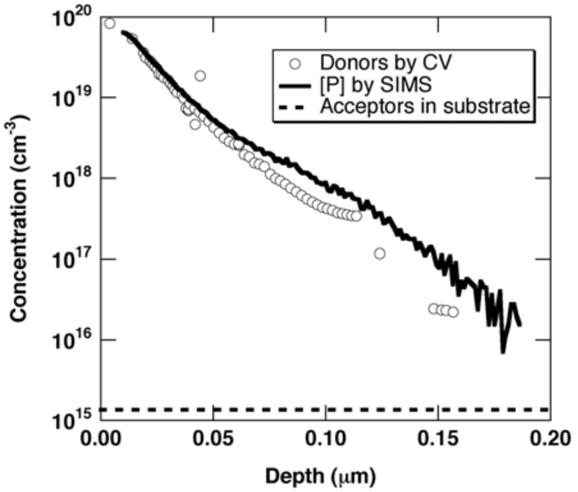

Fig. 4: Profile of donors and phosphorous atoms diffused into silicon substrate during GaNP growth.

secondary ion-mass spectroscopy (SIMS), as well as the net donor concentration profile as measured by electrochemical capacitance-voltage (CV) measurements. From these data, we deduce that the thickness of the diffused emitter in this cell is approximately 2000 Å. This thickness will vary with time and temperature of the III-V growth. An annealed aluminum back contact formed a back-surface field (BSF) in the bottom silicon junction. The aluminum was evaporated on the back after III-V growth, then annealed 5 minutes at 700°C under H_2.

A good tunnel junction on silicon requires extremely high doping levels in GaP or GaNP materials near a sharp interface. Se doping in GaNP is very efficient and high electron concentrations can be achieved, similar to Se doping of GaNAs [11]. P-type doping using Zn or C [9] in GaNP is not well understood and appears problematic. Zn, though, is a common dopant in GaP, and requires low temperatures for high incorporation, so a growth temperature of 600°C was used for the p^+ side of the TJ. The slightly lattice-mismatched GaP layer in this tunnel junction is likely to reduce the crystal perfection of the whole structure if it is too thick, but a lattice-matched layer of sufficiently high p-type doping for a TJ has not yet been achieved.

A 70-nm-thick Se-doped GaAs contact layer was used to make ohmic contact to electroplated gold at the front. This GaAs layer was selectively etched between grids using an NH_3OH : H_2O_2 : H_2O solution. While we have also achieved ohmic contacts to Se-doped GaP and GaNP using annealed Pd/Ge/Pd, the required annealing seems to severely degrade the top junction. The high lattice-mismatch between GaAs and silicon surely results in significant defects in the GaAs layer, but sufficient conduction through the layer is maintained. The extent of these defects that propagate down into the GaNP(As) junction has not yet been characterized.

RESULTS

The current-voltage (IV) and quantum efficiency (QE) performance of the GaNPAs-on-silicon tandem solar cell is shown in Fig. 5. The QEs of the top and bottom junctions were measured separately by light biasing. The IV current was calibrated using the integrated QE of the current-limiting junction (top cell). The IV curves of the top and bottom junctions are also shown separately in Fig. 5. These were measured in nearly identical devices except with inactive junctions. The bottom silicon junction was simulated by doping all the epitaxial layers n-type. The top junction and tunnel junction were simulated together by growing the structure on an n-type silicon substrate. The QE of the single junctions agreed well with the light-bias measurements of the tandem cell.

The tandem solar cell had a V_{oc} of 1.53 V, fill factor of 54%, and J_{sc} of 6.3 mA/cm^2, resulting in an AM1.5G efficiency of 5.2% without any antireflective coatings. The filtered bottom junction had an internal QE of 90% below the band edge of the top cell, a fill factor of 67%, and V_{oc} of 536 mV. The AM1.5G J_{sc} of the bottom silicon junction

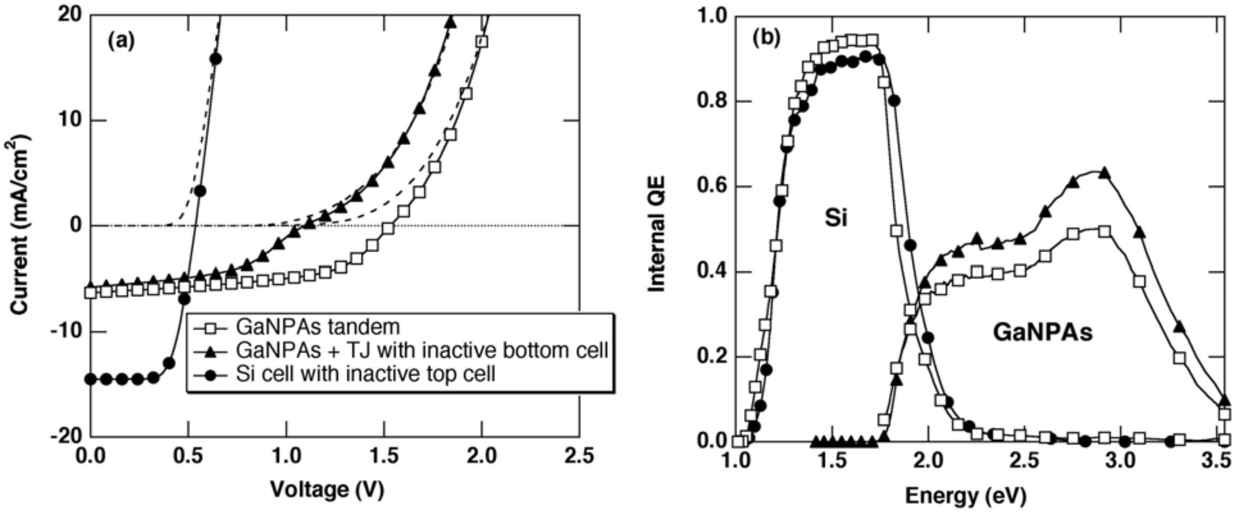

Fig. 5: (a) Light and dark (dashed) IV curves of tandem and single-junction cells. (b) Internal QE of tandem and single-junction cells. Tandem results are light-biased to show both junctions.

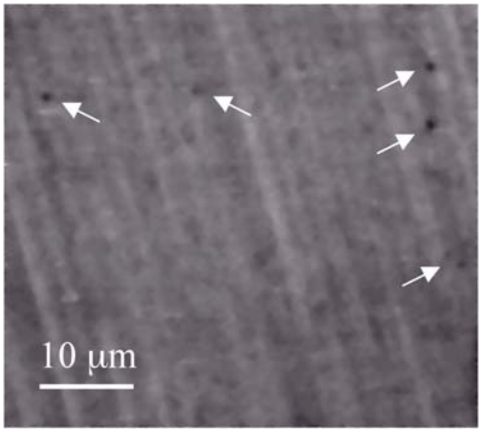

Fig. 6: CL image of top junction of tandem cell grown on silicon. Some of the TDs are indicated by arrows.

was 14.5 mA/cm^2. The top junction had an internal QE of about 40%, a fill factor of 48% and a V_{oc} of 1.09 V. The AM1.5G J_{sc} of the top GaNPAs junction was 5.7 mA/cm^2.

In a separate device, the GaP:Zn / GaNP:Se tunnel junction used here was found to have a specific resistivity of about 1 Ω cm^2. This resistance may be acceptable for one-sun operation, but is inadequate for concentrator applications.

Defects in the top cell grown on silicon were observed using electron-beam-induced current (EBIC) and cathodoluminescence (CL). The CL image shown in Fig. 6 shows threading dislocations (TDs) at a density above 5x10^6 cm^{-2} and misfit dislocations greater than 10^7 cm^{-2}. In contrast, GaNPAs cells grown on GaP contained less than 10^5 cm^{-2} dislocations.

DISCUSSION

The top GaNPAs junction severely limits the current of the tandem device at this point. The bottom silicon junction, on the other hand, is quite respectable for its purpose here. To current match this top cell to the bottom Si cell, we need to increase the QE and/or reduce the band gap of the top cell. Reducing the band gap by increasing nitrogen and arsenic concentration tends to result in lower-quality material and also reduces the J_{sc} of the bottom cell. If a field-aided device is used, increasing the thickness while reducing the carrier concentration in the intrinsic layer may help increase the QE.

Increasing the diffusion length in these materials is the preferable method of increasing the QE. Growth conditions may be further optimized to reduce unintentional carbon and/or hydrogen impurities. Improved nucleation of GaP on silicon may also help by reducing the defect densities.

The tunnel junction remains a significant challenge. Both Se and Zn dopants tend to diffuse quite readily in most III-V semiconductors. Further study of this tunnel junction is required to reliably fabricate GaNPAs-on-silicon tandem cells.

CONCLUSION

We have demonstrated the first lattice-matched III-V on silicon tandem solar cell. For such a tandem solar cell to achieve efficiencies greater than current state-of-the-art silicon cells and compete with GaInP/GaAs/Ge solar cells, the performance of the top GaNPAs junction and tunnel junction must be further improved. These improvements will require better control over nucleation of III-V on silicon substates, doping of GaP and GaNP(As) materials, and material quality of GaNP(As).

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