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# III-V/Silicon Lattice-Matched Tandem Solar Cells

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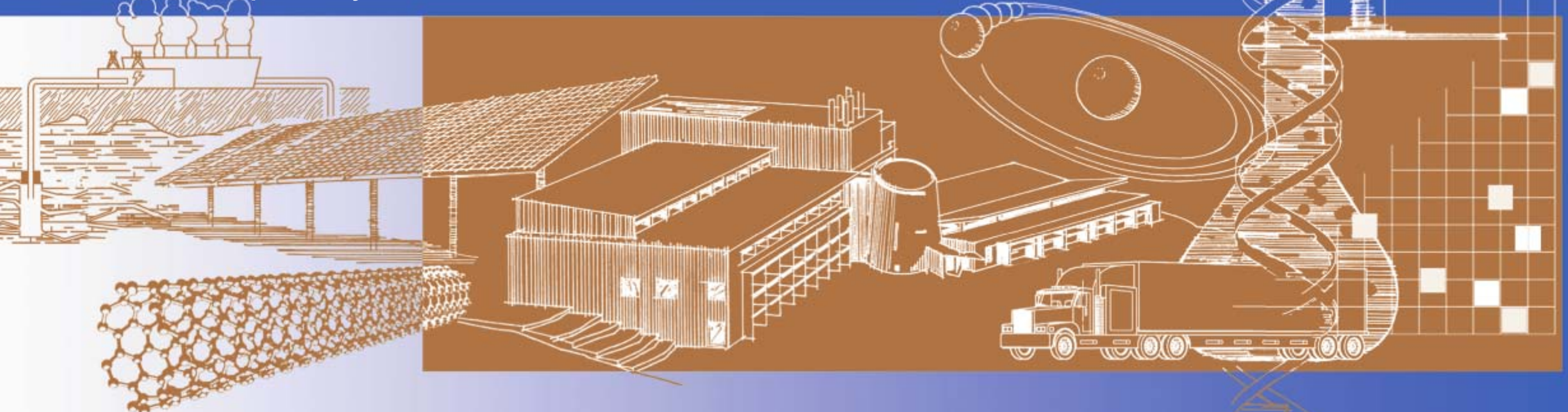

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## ABSTRACT

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 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. To accomplish this, we have developed techniques for the growth of high crystalline quality lattice-matched GaNPAs on silicon by metal-organic vapor-phase epitaxy.

## 1. Objectives

The objective of this research is to develop a high-efficiency, lower-cost multijunction solar cell appropriate for use in concentrated photovoltaic systems. The use of a silicon bottom junction in the silicon substrate leverages the existing silicon technology while reducing the substrate cost. The use of III-V materials in a top junction offers the potential of higher efficiencies than current silicon technology allow, similar to efficiencies currently available only using higher-cost GaAs or Ge substrates. Two-junction solar cell devices using this approach have the potential to reach efficiencies of 35% under the direct spectrum or 37% under the global spectrum.

## 2. Technical Approach

$GaN_xP_{1-x-y}As_y$, hereafter GaNPAs, is a newly discovered direct-gap III-V alloy that can be grown lattice-matched to Si with very low structural defect densities and a band gap ideally suited for a high-efficiency multijunction solar cell. There are many technical challenges to the growth of this semiconductor on silicon to achieve high crystalline and electrical quality in order to realize a high-efficiency multijunction solar cell. In this work, we have made significant progress in understanding and addressing these challenges.

## 3. Results and Accomplishments

*3.1 III-V nucleation and growth on silicon*

The growth of dislocation-free III-V semiconductors on silicon has been a long sought-after goal. The main problem has been the difference in the crystal lattice constant between most III-V alloys and silicon. This difference requires the generation of dislocations to relieve the strain. If these dislocations are located in the active part of a solar cell, many photogenerated electrons recombine at the defects instead of contributing to useful power output. It has recently been demonstrated that by alloying GaN with GaP (and a little GaAs), dislocation-free III-V crystals can be grown [1].

While technically possible, the growth of dislocation-free GaNP(As) on silicon is by no means trivial. Oxide-free silicon surfaces must be prepared in-situ for subsequent III-V growth. The formation of anti-phase domains (APD) must also be avoided. APDs are difficult to avoid because the silicon substrate does not provide a template to determine whether a Ga or P atom should occupy a particular crystal site.

We have employed state-of-the-art analytical techniques to understand the surface of the silicon and subsequent nucleation of GaP within a metal-organic chemical vapor deposition (MOCVD) reactor [2]. These techniques include: reflection-difference spectroscopy, low-energy electron diffraction, x-ray diffraction, Auger electron spectroscopy, scanning-tunneling microscopy, transmission-electron microscopy, and electron-beam induced current.

We have discovered that the use of high temperatures and the tendency of hydrides, such as arsine and phosphine, to etch silicon can be used to remove the silicon oxides. But these tools also can roughen the silicon surface. A smooth silicon surface with well defined step structure is required to suppress the formation of APDs. In addition, the nucleation conditions, such as temperature and pressure, affect whether the first few atomic layers of III-V form a smooth, flat crystal layer or collect into isolated crystal islands.

By taking into consideration all of these effects, we have been able to grow GaNP with fewer than $10^6$ $cm^{-2}$ threading dislocations on silicon (see Fig. 1). The misfit dislocations

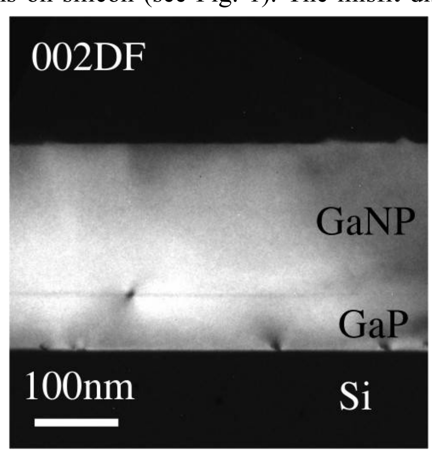


Fig. 1. Transmission electron micrograph of nearly dislocation-free GaNP on silicon.

that remain at this time are typically confined to the Si / GaP interface, so the study of solar cell structures using these materials has also begun. The basic studies required to consistently achieve completely dislocation-free growth remain under way.

*3.2 Tandem solar cells*

Even after dislocation-free III-V material has been achieved on silicon, the fabrication of a lattice-matched III-V-on-silicon solar cell presents many technical challenges [3]. We have overcome many of these challenges and fabricated a two-junction GaNPAs-on-silicon solar cell to satisfy our FY 2004 milestone (see Figs. 2 and 3).

We have shown that the carrier lifetime in GaNP(As) is strongly dependant on the unintentional incorporation of hydrogen and/or carbon [4]. We have developed growth recipes to minimize these unintentional dopants. Even so, the diffusion length in these materials remains low, requiring the use of field-aided collection at this time. A thick intrinsic layer is thus used in the current top junction. These issues result in internal quantum efficiencies (QE) on the order of 50%. A reduction in the band-gap of the active GaNPAs layer is also required to increase the $J_{sc}$ of the top cell. Understanding the reason for short diffusion lengths remains an important field for continued study.

A diffused homojunction is formed in boron-doped (p-type) CZ silicon substrates during the nucleation and growth of the III-V. The junction depth is typically about 0.2 m. The front passivation of the silicon emitter should depend strongly on the density of defects at the Si / GaP interface, but because most of the blue light is captured by the top cell, imperfect front passivation does not strongly degrade the $J_{sc}$ of the Si junction. Back passivation is provided by an annealed Al contact similar to that of typical silicon solar cells. The $V_{oc}$ of the silicon bottom junction is currently about 535mV with a GaNPAs filter. Improvement of the $V_{oc}$ may be made by further reduction of the Si / GaP interface defect density.

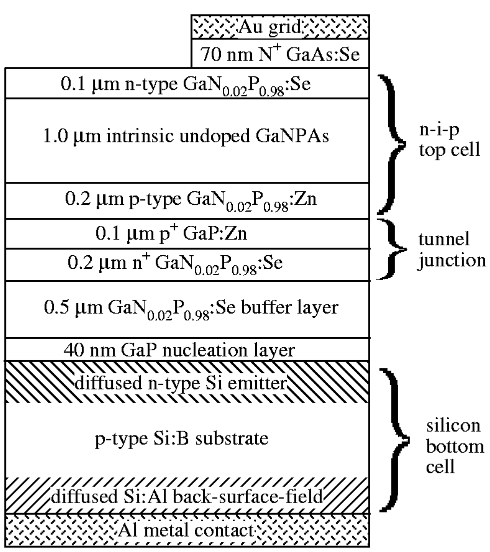


Fig. 2. Schematic of III-V-on-silicon tandem solar cell

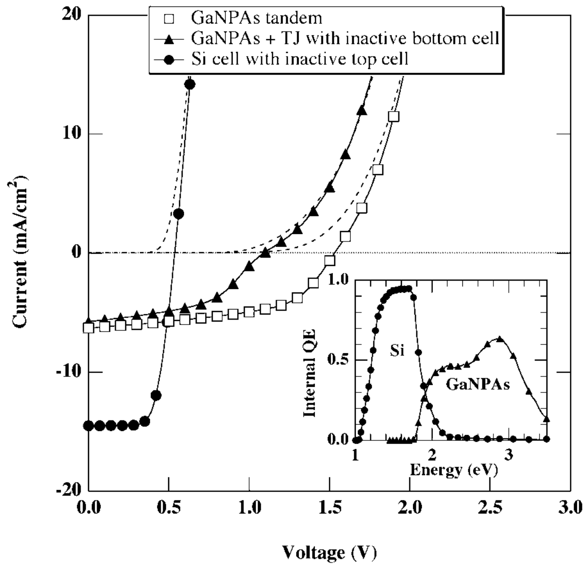


Fig. 3. IV and QE measurements of III-V-on-silicon tandem solar cell and its component junctions.

A n-GaNP/p-GaP tunnel junction is used as a low-resistance interconnect between junctions. Achieving sufficiently high carrier concentrations in both sides of this tunnel junction is a significant challenge. We have developed a tunnel junction that is sufficient for one-sun use, but may require further improvement for concentrator use.

## 4. Conclusions

We have satisfied a FY 2004 milestone by fabricating a functioning two-junction GaNPAs-on-silicon solar cell. Continued basic and applied studies are required to further reduce the dislocation densities and increase the top cell current in order to achieve high efficiencies.

## ACKNOWLEDGEMENTS

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