

# Nanoparticle-Enhanced Tunnel Junctions for High-Efficiency Multi-Junction Solar Cells

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## Abstract:

Multi-junction solar cells employ tunnel junctions to interconnect the serially-connected p/n junctions. Erbium arsenide nanoparticle (ErAs NP)-enhanced tunnel junctions, grown on gallium arsenide, have Schottky-like tunneling barriers that show substantial improvements in tunneling current density, when compared to conventional p/n junctions. Future multi-junction solar cells incorporate dilute-nitrides to achieve technologically significant band-gaps, which require thermal annealing to remove point defects from the gallium indium nitride arsenide (GaInNAs) lattice. Preliminary data indicates that post growth thermal annealing can enhance the tunneling currents of nanoparticle-enhanced tunnel junctions; however, thermal annealing has not been carefully studied. We are performing the first careful study of thermal annealing, consisting of an *in situ* and *ex situ* study. Results of the study suggest erbium arsenide tunnel junctions improve with thermal annealing.

## Introduction:

A single p/n junction extracts one band-gap of energy per photon. Multi-junction solar cells use multiple junctions to divide the solar spectrum and increase efficiency. Tunnel junctions are used to serially interconnect p/n junctions. Current multi-junction solar cell design incorporates an overdriven germanium (Ge) junction. Adding a 1.0 electron volt material junction bifurcates the Ge junction without a substantial loss in junction performance. Dilute-nitrides are a potential candidate for the new junction material. As seen in Figure 1, GaInNAs can achieve the technologically significant 1.0 electron volt band-gap while maintaining the same lattice parameter as gallium arsenide (GaAs). However, GaInNAs requires a post-growth thermal anneal to reduce point defects.

Conventional tunnel junctions are formed from a heavily doped p/n junction. However, there is a doping limit due to material properties. Erbium arsenide (ErAs) nanoparticles deposited at the p/n junction form back-to-back Schottky contacts and leads to a significant improvement in tunneling current density. As shown in Figure 2, incorporating ErAs nanoparticles at the p/n junction effectively splits the tunneling barrier, reducing height and width. In order to function in a multi-junction solar cell, erbium arsenide nanoparticles must be robust to thermal annealing associated with dilute-nitrides. We are performing the first in-depth thermal annealing study of erbium arsenide nanoparticle-enhanced tunnel junctions.

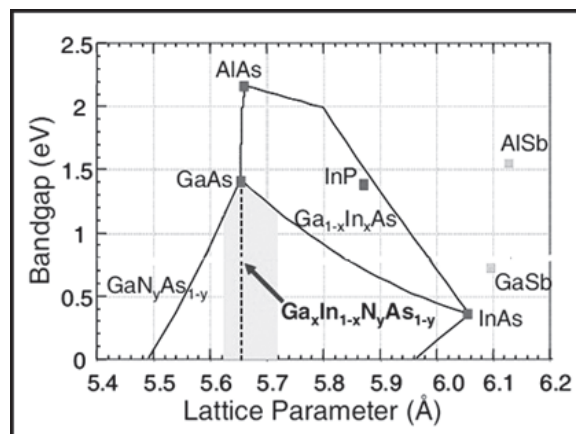


Figure 1: Band-gap versus lattice parameter for various semiconductors. GaInNAs varies with composition.

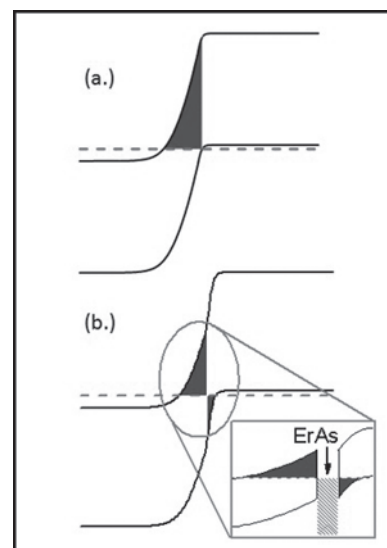


Figure 2: Band diagram of; (a) a conventional heavily doped p/n tunnel junction, and (b) an ErAs NP-enhanced tunnel junction. The shaded triangular regions represent the tunneling barriers.

## Experimental Procedure:

We performed an *in situ* and an *ex situ* annealing study to mimic the conditions of multi-junction solar cell growth and the post-growth anneal required for dilute-nitrides. Heavily n-doped GaAs, ErAs NPs, followed by heavily p-doped GaAs were deposited on an n-doped GaAs substrate using molecular beam epitaxy. The *in situ* anneal occurred at 600°C under an arsenic flux. The *ex situ* anneal was performed in a rapid thermal annealer at varying temperatures for one minute under a nitrogen flux. For top contact lithography, we employed an image reversal photoresist, AZ 5214E-IR.

Immediately prior to both metallizations, the samples were treated with a hydrochloric acid to remove the native oxide. E-beam evaporation was employed for metallization; the top p-type contact consisted of 100 angstroms (Å) of titanium followed by 1000 Å of gold (Au). Liftoff took approximately 30 minutes in an agitated acetone bath. Bottom contact metallization consisted of 100 Å Au, 100 Å Ge, 100 Å nickel (Ni), and 1000 Å Au. The bottom contact metallization requires thermal treatment to improve contact quality. P-type and n-type doping calibration wafers were measured using the transmission line method to verify contact performance. Both the n-type and p-type contact showed acceptable performance after a 400°C anneal for one minute. After metallization, an inductively coupled plasma etch was used to etch through and isolate the tunnel junctions to improve measurement accuracy.

Measurements were taken using a four-point probe station to reduce parasitic resistance present in the probes. Two low resistance probes pushed current, while two high resistance probes measured the voltage difference. Current to voltage measurements were taken on circles of known radius. Tunnel junction resistance dominates for small mesa diameters. Therefore, a 35 nm diameter mesa was measured to extract the current density.

As shown in Figure 3, the *ex situ* annealed samples showed a substantial improvement in tunnel junction quality. The *in situ* annealing study, shown in Figure 4, also yielded an improvement in tunnel junction performance.

## Results and Conclusions:

We have demonstrated erbium arsenide nanoparticle-enhanced tunnel junctions do not degrade, and in fact improve for both the *in situ* and *ex situ* anneal. The *ex situ* anneal demonstrates ErAs tunnel junctions are compatible with growth conditions of multi-junction solar cells. Whereas the *in situ* demonstrates the tunnel junctions are compatible with the post growth thermal anneal required for dilute-nitrides. The resulting tunnel junction resistance is acceptable for use in high-efficiency multi-junction solar cells. A publication will be prepared once a more complete thermal study and other ancillary experiments are performed.

Eventually, we would like to create a multi-junction solar cell incorporating both ErAs nanoparticle-enhanced tunnel junctions and dilute-nitrides.

## Acknowledgements:

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## References:

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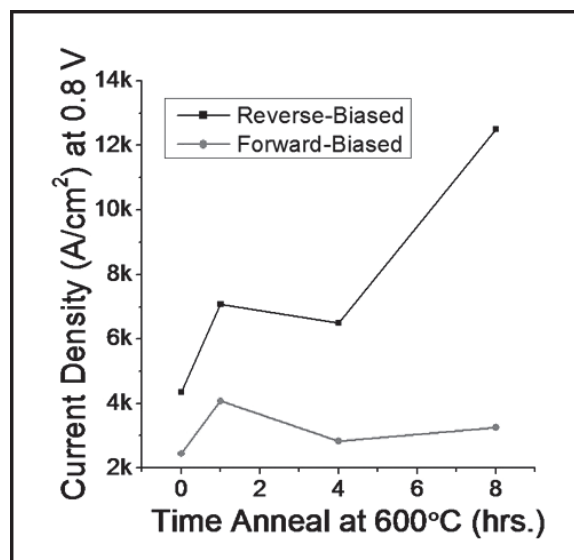


Figure 3: *In situ* anneal data at 0.8 volts.

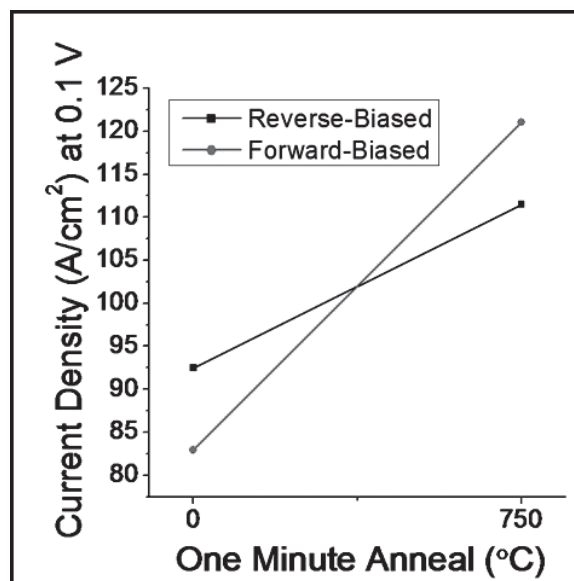


Figure 4: *Ex situ* anneal data at 0.1 volts.