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Demonstration of a III–Nitride/Silicon Tandem Solar Cell

Lothar A. Reichertz[1], Iulian Gherasoiu[2], Kin Man Yu[1], Vincent M. Kao[1],
Wladek Walukiewicz[1,2], and Joel W. Ager III[1]*

[1] *Materials Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, U.S.A.*
[2] *RoseStreet Labs Energy, 3701 E. University Dr., Phoenix, AZ 85034, U.S.A.*

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We report on the proof of principle of a III–nitride/silicon tandem solar cell. Photovoltaic activity is demonstrated in a 0.25 cm^2 dual junction solar cell, made of p- and n-type GaN layers which were grown by molecular beam epitaxy (MBE) on a standard n-type Si wafer with an Al doped p-type surface. An open circuit voltage (V_{oc}) of 2.4 V was measured under 1× sun AM1.5G condition with additional UV laser illumination of the GaN junction. Experiments under various illumination conditions were performed to verify that both junctions are active and working in series.

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Tandem solar cells using semiconductors with a range of bandgaps hold the current 1× sun AM1.5G conversion efficiency world record of 33.8%;[1)] values over 40% are achieved with concentration.[2)] Tandems with Si as bottom cell were proposed in the early 1980s, and an AlGaAs/Si tandem was demonstrated previously with an efficiency of 21%.[3)] The bandgap of InGaN is tunable over nearly the entire useful range of the solar spectrum (0.65 to 3.4 eV) and is therefore an ideal candidate for part or all of a multijunction solar cell.[4)] A tandem cell using InGaN for the top cell and Si for the bottom cell is advantageous in two respects: (1) the InGaN bandgap can be tuned to 1.8 eV to provide current matching and to optimize the performance of the tandem with the Si bottom cell; and (2) the alignment on an absolute energy scale of the InGaN conduction band and the Si valence band should produce a low resistance tunnel junction.[5)] For this system with realistic values of diffusion lengths, etc., predicted efficiencies approach 30%.[6)] Recently, we have verified that Al diffusion into the silicon substrate during the growth of nitride layers forms a viable silicon solar cell and we have demonstrated a low series resistance of the nitride–silicon heterojunction.[7–9)] Here we present the first evidence of tandem solar cell performance in a nitride/silicon cell. The demonstration is performed with a GaN/Si tandem that, while theoretically limited to an AM1.5G conversion efficiency of 1.5% because of the large GaN bandgap, shows definitively the additivity of the subcell photovoltages.

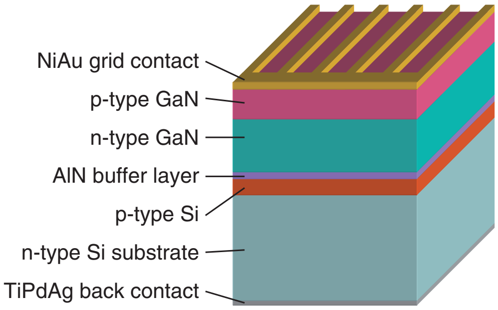

Fig. 1. Schematic of the GaN/Si tandem solar cell prototype.

The protoype III–nitride/silicon tandem cell structure illustrated schematically in Fig. 1 was grown and optimized using a high productivity, plasma-assisted molecular beam epitaxy (PA-MBE) system at RoseStreet Labs Energy in Phoenix, AZ. In order to accommodate the lattice mismatch between Si and GaN, a thin AlN buffer layer was first grown on the n-type Si(111) wafer. As a by-product of the AlN layer formation, the surface of the Si wafer becomes heavily p-type doped through Al in-diffusion. This generates the pn-junction that forms the Si bottom cell. On top of the AlN buffer, an about 500 nm thick, nominally undoped GaN layer was grown. This layer is n-type with an electron concentration in the 10^{17} cm^{-3} range. Then the Mg source was turned on and a thin p-type GaN:Mg layer completed the growth of the dual junction structure. Photolithography and an electron beam evaporator was used to deposit NiAu (20/60 nm) in grid patterns as the front contact on the p-type GaN top layer. TiPdAg (15/15/400 nm) was electron beam evaporated onto the back side of the Si wafer as back contact. Finally, 5 × 5 mm^2 prototype cells were diced from the wafer.

A low resistance junction for the recombination of electrons from the n-type GaN (or InGaN) with the holes from the p-type Si is important for this tandem solar cell. Therefore, we grew several control structures with only undoped GaN layers on Si(111). In such devices only the pn junction in the Si generates photocurrent; thus the structure can be used to test the functionality of the GaN-Si recombination junction. In these single junction cells, we typically measure open circuit voltages (V_{oc}) in the range of 500 to 550 mV and short circuit current densities (J_{sc}) of 20 to 25 mA/cm^2 under illumination from a 1× Sun AM1.5G simulator. The I–V curve for such a n-GaN/pn-Si structure is shown in Fig. 2. An efficiency of 9.3% for this sample was measured with a total series resistance of 0.5 Ω cm^2 proving the effectiveness of the tunnel junction.

It is important to notice that a complete pn-GaN/pn-Si tandem cell is expected to have a significantly lower AM1.5G conversion efficiency than the control structure. Since only a fraction of the terrestrial solar spectrum extends above the GaN bandgap of 3.4 eV, a functional GaN pn-junction will restrict the current at 1× sun AM1.5G to a theoretical maximum of 0.6 mA/cm^2 (100% quantum efficiency for photons energies greater than 3.4 eV). With this current limit an upper limit for the theoretical conversion efficiency can be estimated. Combining realistic values for the V_{oc} (2.6 V plus 0.55 V) and estimating a fill factor of 80% would yield an upper efficiency limit of only

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*E-mail address: JWAger@lbl.gov

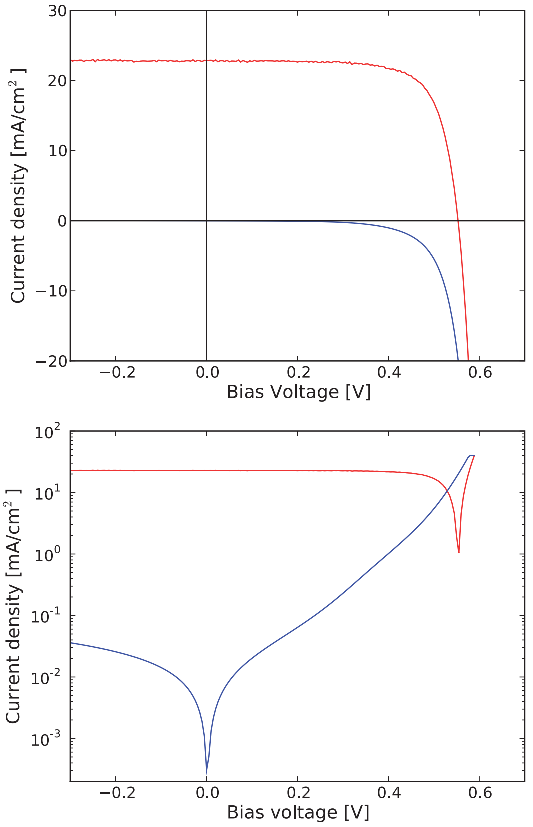

Fig. 2. Linear and semilog *I*–*V* curves of a n-GaN/pn-Si control structure (no tandem) under 1× sun AM1.5G illumination (red curve) and in the dark (blue curve), V_{oc} = 555 mV, J_{sc} = 22.9 mA/cm^2, Fill factor = 73%, series resistance = 0.5 Ω cm^2, Conversion efficiency = 9.3%.

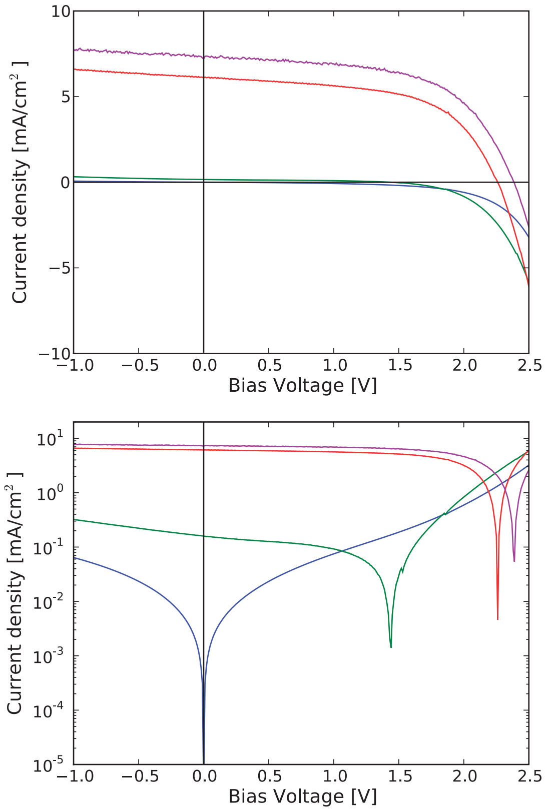

Fig. 3. Linear and semilog *I*–*V* curves of the pn-GaN/pn-Si tandem solar cell structure under different illumination conditions: dark (blue), 1× sun AM1.5G (green), 20× sun AM1.5G (red), 1× sun AM1.5G plus 325 nm UV laser (magenta).

1.5%. The scope of this paper is therefore to demonstrate a working nitride-Si tandem cell by showing a significant increase in voltage compared to a single Si cell. For higher efficiencies the subcells have to be current matched by optimizing the band gap of the top cell. Figure 3 shows *I*–*V* curves of the full pn-GaN/pn-Si tandem structure described in this article. Already with 1× sun AM1.5G illumination we measured a V_{oc} of 1.44 V, more than 2.5 times the voltage of our Si bottom cell. The short circuit current density ($J_{sc} = 0.16\,\mathrm{mA/cm^2}$) under 1× AM1.5G is, as expected, over two orders of magnitude lower than in the control structure. In fact, this *I*–*V* relation shows that the GaN top cell is actually operating and is restricting the current that is generated in the Si bottom cell. In this current restricting mode we measured a fill factor of 40%, limiting the 1× sun AM1.5G efficiency to 0.1%.

Two different methods were applied to increase the top cell current. First, the AM1.5G light from the solar simulator was concentrated to about 20×. Second, above bandgap illumination with a HeCd laser at 325 nm was used in addition to the 1× AM1.5G. Under concentration the V_{oc} increased from 1.44 to 2.26 V and J_{sc} from 0.16 to 6.14 mA/cm^2. For 1× sun plus 30 mW 325 nm HeCd laser light the V_{oc} reached a maximum of 2.40 V and the maximum J_{sc} was 7.3 mA/cm^2. The fill factor increased to 59%. These values provides direct evidence for tandem action in the structure. In a control experiment, additional illumination with a HeCd laser at 442 nm (below the GaN bandgap) was tested and no increase at all in V_{oc} and J_{sc} over the 1× sun case was detected. This also confirms the large current mismatch between the bottom and the top cell. The bottom cell is able to provide much more current already from 1× sun only and therefore no change is seen from additional 442 nm illumination.

Based on reports of V_{oc}s of *ca.* 2.6 V in GaN pn junction devices[5,10] we might expect an even higher V_{oc} for our tandem structure. We believe that high recombination rates and therefore short minority carrier lifetimes in combination with a small depletion width are the main reasons for limitations, since doping levels and crystal quality of the GaN are not optimized yet. With an absorption coefficient of $\alpha = 10^5\,\mathrm{cm}^{-1}$ for GaN, a thickness of 500 nm absorbs more than 99% of the photons with energies above the GaN bandgap. However, using reasonable estimates for doping levels in our material we calculate a depletion width of about 100 nm. A doping level below $10^{17}\,\mathrm{cm}^{-3}$ would be necessary to deplete a significant fraction of the layer for optimum efficiency. The small width of the depletion region in combination with the short diffusion length alone already reduces the carrier collection efficiency theoretically to less than 40%. This supposition is supported by the fact that we see an increase of current under reverse bias which enhances carrier collection by increasing the depletion width. For example, a pn-GaN control sample showed an about 20% increase in external quantum efficiency under a reverse bias of 1.6 V versus an unbiased measurement. The steady increase in photo current with reverse bias could also be partially from a less than optimum value for the shunt

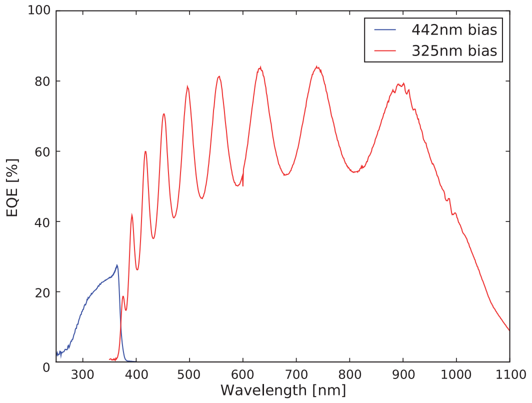

Fig. 4. External quantum efficiency spectra of the pn-GaN/pn-Si tandem solar cell under different bias light conditions. Monochromatic bias light is used to separately measure each sub cell.

resistance in the top cell, which would further reduce the V_{oc}. Work is underway to address all these issues.

The tandem activity was studied in more detail by performing quantum efficiency measurements. External quantum efficiency was measured using a 150 W xenon lamp and a grating monochromator. The light from the xenon lamp was modulated with a chopper allowing to extract the cells photovoltaic (PV) response to the monochromator output by a lock-in amplifier. A silicon photodiode with a NIST traceable spectral response calibration was used to calibrate the modulated photon flux at each wavelength incident on the solar cell. The setup also allowed the illumination of the sample during the spectral scan with additional unmodulated light (bias light) from a HeCd laser running at either 325 nm (above the GaN bandgap energy) or at 442 nm (below the GaN bandgap energy). This enabled to selectively measure the quantum efficiency of one sub cell by light biasing only the other sub cell that was not under test.

Figure 4 shows external quantum efficiency (EQE) spectra separately for each sub cell of the pn-GaN/pn-Si tandem structure. Since the band gap energy of GaN lies in the UV (365 nm) most of the solar spectrum reaches the Si sub cell. The large difference between the area under the Si curve (red) and the area under the GaN curve (blue) illustrates the current mismatch between the two sub cells. Fabry Perot oscillations according to thickness and refractive index of the GaN film indicate a high optical quality of the GaN surface that increases reflection losses. These losses can be reduced by a rougher (textured) surface in future cells. Under constant 325 nm illumination, used to bias the GaN cell, the quantum efficiency measured for the Si cell is lower than optimum but still remarkably high in comparison to the very low total current under 1× sun AM1.5G. This discrepancy is again a consequence of the large current mismatch between the two sub cells. The maximum possible current is already reached for a low level illumination of the Si cell and hence the quantum efficiency drops drastically at 1× sun illumination.

When the tandem cell was illuminated by the 442 nm laser line in order to generate a constant background of bias light only for the Si sub cell, the response to the additional modulated monochromatic light dropped to basically zero everywhere below the GaN bandgap energy, as the current is already saturated from the unmodulated bias light. However, additional (modulated) monochromatic light *above* the GaN bandgap increased the current in the restricting top cell and is therefore detected by the lock-in amplifier as a modulated signal. Therefore, the blue curve in Fig. 4 shows a clear cut-on at the GaN bandgap energy (365 nm) and represents the quantum efficiency spectrum of the GaN top cell. This efficiency peaks at almost 30% at the band edge and decreases gradually toward higher photon energies. As UV photons with increasingly higher energies penetrate less and less deep into the material, it appears that a pn-junction located closer to the surface would be beneficial for carrier collection; thus leading ultimately to a higher efficiency of the GaN top cell.

In conclusion, we have experimentally demonstrated a functioning GaN/Si tandem solar cell as a proof of principle for future fabrication of high performance III–nitride solar cells. The low conversion efficiency measured is attributed mainly to the high bandgap of GaN in relation to the terrestrial solar spectrum. Ongoing work in our group is focused on tuning the top cell bandgap by incorporating In during growth in order to fabricate a nitride/silicon tandem with current matched sub cells.

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