
# High-Efficiency Amorphous and Nanocrystalline Silicon Based Solar Cells and Modules

*Subhendu Guha and Jeffrey Yang*
*United Solar Ovonic LLC*

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# Relevance/Objective

- **Objectives and Relation to the DOE SETP Multi-year Program Plan**

1. Optimize the a-Si:H and a-SiGe:H deposition parameters under the current manufacturing constraints for improving the solar module efficiency and manufacturing throughput, and reducing the manufacturing cost

   →Addresses the short-term goal

2. Explore new deposition methods for a-Si:H and a-SiGe:H materials to improve the a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cell efficiency at high deposition rates

   →Addresses the mid-term goal

3. Explore new materials and new cell structures for higher efficiency at high deposition rate

   →Addresses the long-term goal

# Summary of Activities

- **Main Activities**

1. Optimize the a-Si:H and a-SiGe:H component cells as well as the a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells using a large-area batch RF glow discharge reactors. When experimental deposition parameters are improved, the new recipe will be transferred to the production lines.

2. Study high rate a-Si:H and a-SiGe:H solar cell deposition with a modified very high frequency (MVHF) glow discharge deposition technique.

3. Optimize the nc-Si:H material and solar cells deposited using MVHF glow discharge at high rates.

# Budget History

| Project Phases | Total Value |
|---|---|
| Phase I<br>Jan. 2006-Jan. 2007 | $1,991,848 |
| Phase II<br>Jan. 2007-Jan.2008 | $1,991,848 |
| Phase III<br>Jan. 2008-Jan. 2009 | $1,991,848 |
| **Grand Total** | $5,975,544 |

# Accomplishments

- **Major Accomplishments**

1. **Achieved an aperture-area stable efficiency of 8.6% on an a-Si:H/a-SiGe:H/a-SiGe:H triple-junction solar cell deposited under the manufacturing constraints on an Al/ZnO back reflector. The a-SiGe:H layers were made with a $SiH_4/GeH_4$ gas mixture.**

2. **Optimized the deposition parameters for a-Si:H and a-SiGe:H deposition with MVHF at high rates and found that the performance and stability of a-Si:H single-junction cells deposited using MVHF do not depend on the deposition rate in the range of 1-15 Å/s.**

3. **Achieved active-area (0.25 $cm^2$) initial and stable efficiencies of 9.0% and 8.5%, respectively, for nc-Si:H single-junction cells made with MVHF at a high rate ~ 5-8 Å/s.**

# Accomplishments

- **Major Accomplishments-Continue**

4. **Achieved active-area (0.25 $cm^2$) initial and stable efficiencies of 15.1% and 13.0%, respectively, for an a-Si:H/a-SiGe:H/nc-Si:H triple-junction cell, where the top and middle cells were made using RF at a low rate ~ 1 Å/s, and the nc-Si:H bottom cell using MVHF at a high rate ~ 5-8 Å/s.**

5. **Achieved active-area (0.25 $cm^2$) initial and stable efficiencies of 14.1% and 13.3%, respectively, for an a-Si:H/nc-Si:H/nc-Si:H triple-junction cell, where the top cell was made using RF at a low rate ~ 1 Å/s, and the nc-Si:H middle and bottom cells using MVHF at a high rate ~ 5-8 Å/s.**

6. **Demonstrated that an optimized hydrogen dilution profiling not only improves the initial nc-Si:H cell performance but also the stability against light soaking.**

# Accomplishments

- **Major Accomplishments-Continue**

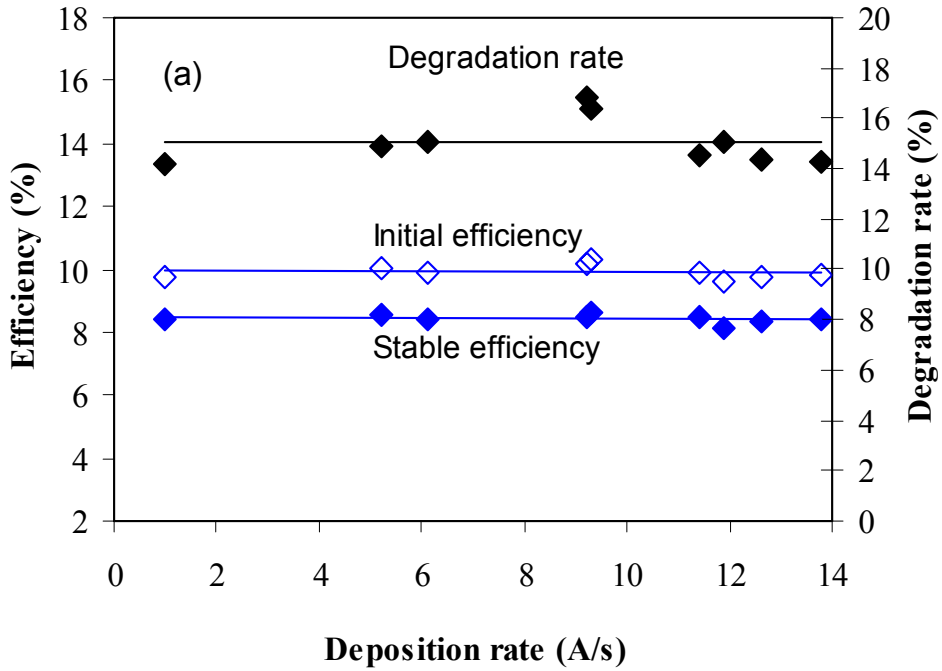
## a-Si:H/a-SiGe:H/a-SiGe:H Triple-Junction modules

| Sample No. | State | Area ($cm^2$) | $I_{sc}$ (A) | $J_{sc}$ ($mA/cm^2$) | $V_{oc}$ (V) | FF | $P_{max}$ ($mW/cm^2$) |
|---|---|---|---|---|---|---|---|
| 10386 | Before lamination | 420.0 | 2.960 | 7.05 | 2.190 | 0.654 | 10.08 |
| | After lamination | 413.8 | 2.882 | 6.96 | 2.180 | 0.662 | 10.04 |
| | Stable | 413.8 | 2.813 | 6.80 | 2.090 | 0.599 | 8.51 |
| 10383 | Before lamination | 420.0 | 2.947 | 7.02 | 2.210 | 0.662 | 10.24 |
| | After lamination | 416.0 | 2.876 | 6.91 | 2.180 | 0.671 | 10.11 |
| | Stable | 416.0 | 2.811 | 6.76 | 2.100 | 0.609 | 8.63 |
| 11156 | Before lamination | 462.0 | 3.382 | 7.32 | 2.230 | 0.645 | 10.53 |
| | After lamination | 458.0 | 3.239 | 7.07 | 2.220 | 0.654 | 10.25 |
| | Stable | 458.0 | 3.231 | 7.05 | 2.120 | 0.569 | 8.50 |
| 11166 | Before lamination | 462.0 | 3.349 | 7.25 | 2.230 | 0.650 | 10.47 |
| | After lamination | 458.0 | 3.215 | 7.02 | 2.210 | 0.651 | 10.10 |
| | Stable | 458.0 | 3.176 | 6.93 | 2.110 | 0.578 | 8.47 |

**Triple-junction a-Si:H/a-SiGe:H/a-SiGe:H modules (> 400 $cm^2$) made with $SiH_4/GeH_4$ mixtures under manufacturing constraints.**

- **Major Accomplishments-Continue**

## MVHF a-Si:H Single-Junction Solar Cells




Initial and stable efficiencies of MVHF deposited a-Si:H cells, as well as their degradation rate, as a function of the deposition rate.

- # Major Accomplishments-Continue

## MVHF nc-Si:H Single-Junction Solar Cells

| Sample No. | Status | $V_{oc}$ (V) | $J_{sc}$ (mA/cm$^2$) | FF | $P_{max}$ (mW/cm$^2$) |
|---|---|---|---|---|---|
| 13310 | Initial | 0.564 | 23.08 | 0.632 | 8.23 |
| | Stable | 0.561 | 21.78 | 0.644 | 7.80 |
| 13348 | Initial | 0.544 | 22.72 | 0.660 | 8.16 |
| | Stable | 0.543 | 21.81 | 0.661 | 7.83 |
| 13461 | Initial | 0.559 | 23.34 | 0.640 | 8.35 |
| | Stable | 0.553 | 22.87 | 0.646 | 8.17 |

nc-Si:H single junction solar cells with 30 minutes of intrinsic layer deposition time .

# Accomplishments

- **Major Accomplishments-Continue**

## MVHF nc-Si:H Single-Junction Solar Cells

| Sample No. | State | $J_{sc}$ (mA/cm$^2$) | $V_{oc}$ (V) | FF | $P_{max}$ (mW/cm$^2$) |
|---|---|---|---|---|---|
| 13821 | Initial | 23.86 | 0.574 | 0.640 | 8.77 |
| | Stable | 22.86 | 0.569 | 0.641 | 8.34 |
| 13829 | Initial | 23.11 | 0.566 | 0.648 | 8.48 |
| | Stable | 22.25 | 0.564 | 0.650 | 8.16 |
| 13831 | Initial | 23.59 | 0.568 | 0.671 | 8.99 |
| | Stable | 23.02 | 0.562 | 0.659 | 8.53 |

nc-Si:H single junction solar cells with one hour of intrinsic layer deposition time.

# • Major Accomplishments-Continue

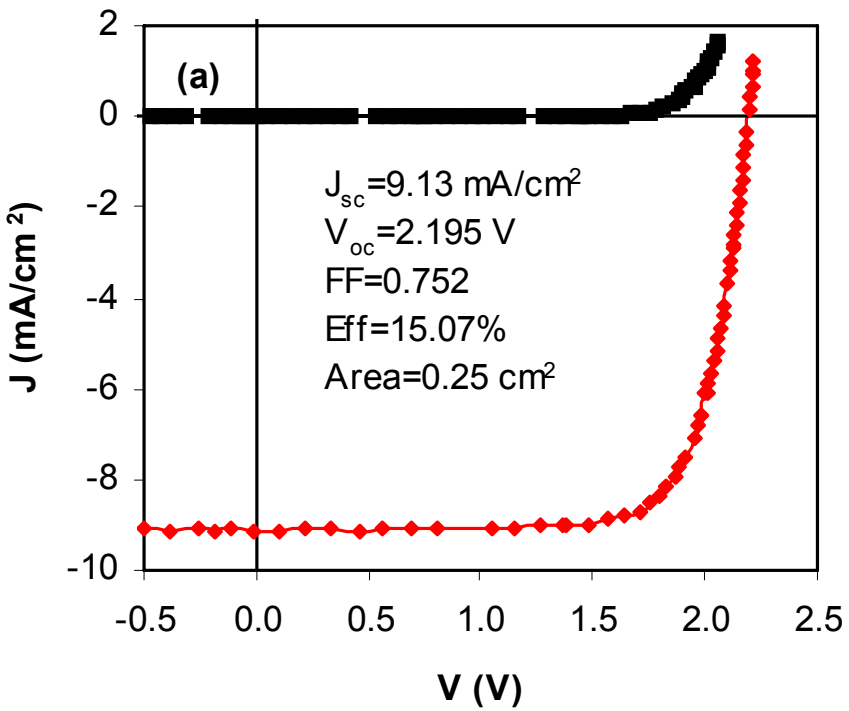
## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells

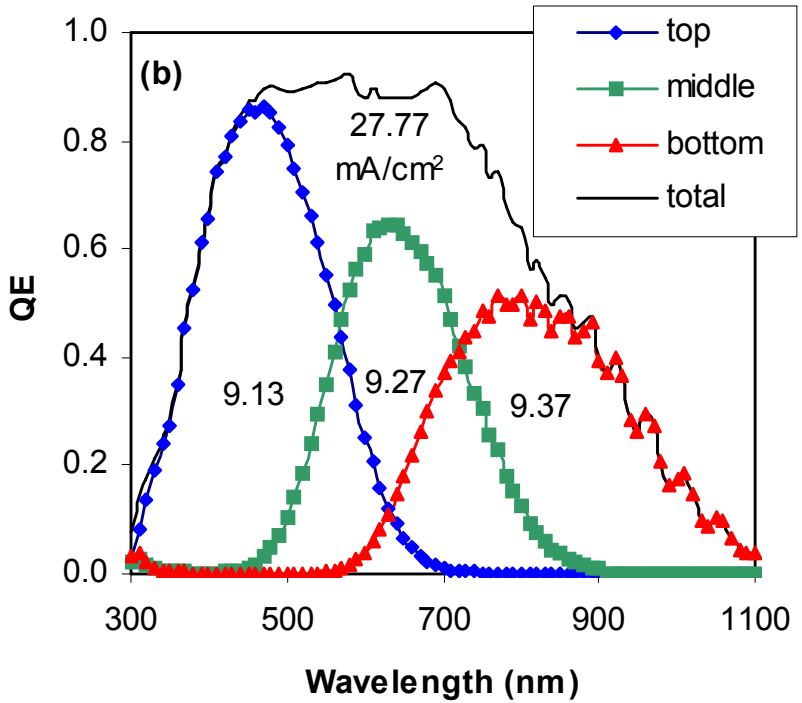
| Sample | State | $J_{sc}$ (mA/cm²) | QE (mA/cm²) | | | FF | $V_{oc}$ (V) | Eff (%) |
|---|---|---|---|---|---|---|---|---|
| | | | top | middle | bottom | | | |
| 15501-34 | Initial | 9.11 | *9.11* | 9.24 | 9.26 | 0.756 | 2.145 | 14.77 |
| | Degraded | 8.71 | 8.99 | *8.71* | 9.12 | 0.700 | 2.087 | 12.72 |
| 15506-33 | Initial | 9.13 | *9.13* | 9.27 | 9.37 | 0.752 | 2.195 | 15.07 |
| | Degraded | 8.81 | 8.90 | *8.81* | 9.26 | 0.690 | 2.091 | 12.71 |
| 15506-34 | Initial | 8.72 | 9.25 | 9.41 | *8.72* | 0.755 | 2.167 | 14.27 |
| | Degraded | 8.71 | 8.97 | 8.81 | *8.72* | 0.704 | 2.011 | 12.98 |

**Triple junction solar cells with an a-Si:H/a-SiGe:H/nc-Si:H structure, where the deposition time of the bottom nc-Si:H intrinsic layers was 1 hour.**

- # Major Accomplishments-Continue

## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells




**Initial J-V characteristics and QE curves of an a-Si:H/a-SiGe:H/nc-Si:H structure.**

# • Major Accomplishments-Continue

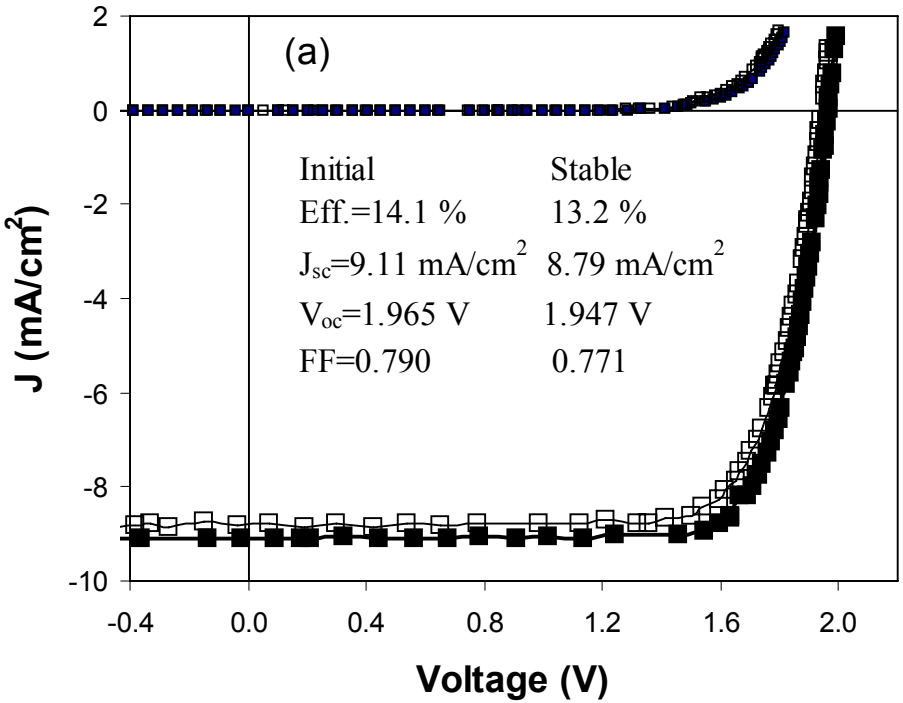
## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells

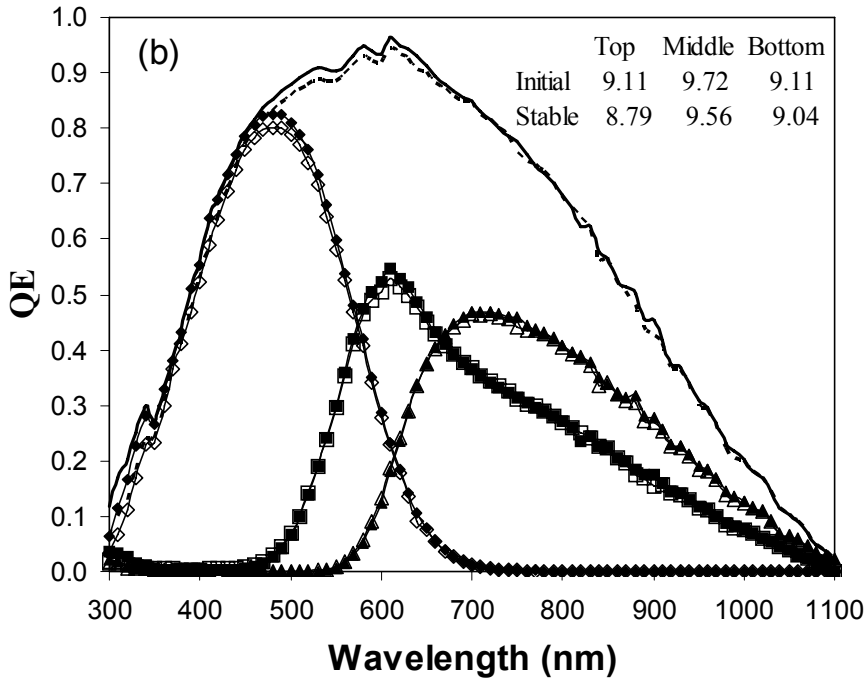
| Sample No. | State | Eff. (%) | $V_{oc}$ (V) | FF | $J_{sc}$ (mA/cm$^2$) | Q(mA/cm$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Top | Middle | Bottom | Total |
| 13955-33 | Initial | 14.1 | 1.965 | 0.790 | 9.11 | 9.11 | 9.72 | 9.11 | 27.94 |
| | Stable | 13.2 | 1.947 | 0.771 | 8.79 | 8.79 | 9.56 | 9.04 | 27.39 |
| 13955-24 | Initial | 13.9 | 1.981 | 0.787 | 8.89 | 9.02 | 9.52 | 8.89 | 27.43 |
| | Stable | 13.3 | 1.973 | 0.771 | 8.72 | 8.75 | 9.25 | 8.72 | 26.72 |
| 14005-33 | Initial | 13.7 | 1.944 | 0.782 | 8.99 | 9.44 | 9.54 | 8.99 | 27.97 |
| | Stable | 13.2 | 1.933 | 0.768 | 8.92 | 9.04 | 9.42 | 8.92 | 27.38 |

**Triple junction solar cells with an a-Si:H/nc-Si:H/nc-Si:H structure, where the deposition time for both the middle and bottom cell intrinsic layers was 1 hour.**

- # Major Accomplishments-Continue

## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells




**Stable J-V characteristics and QE curves of an a-Si:H/nc-Si:H/nc-Si:H structure.**

# • Major Accomplishments-Continue

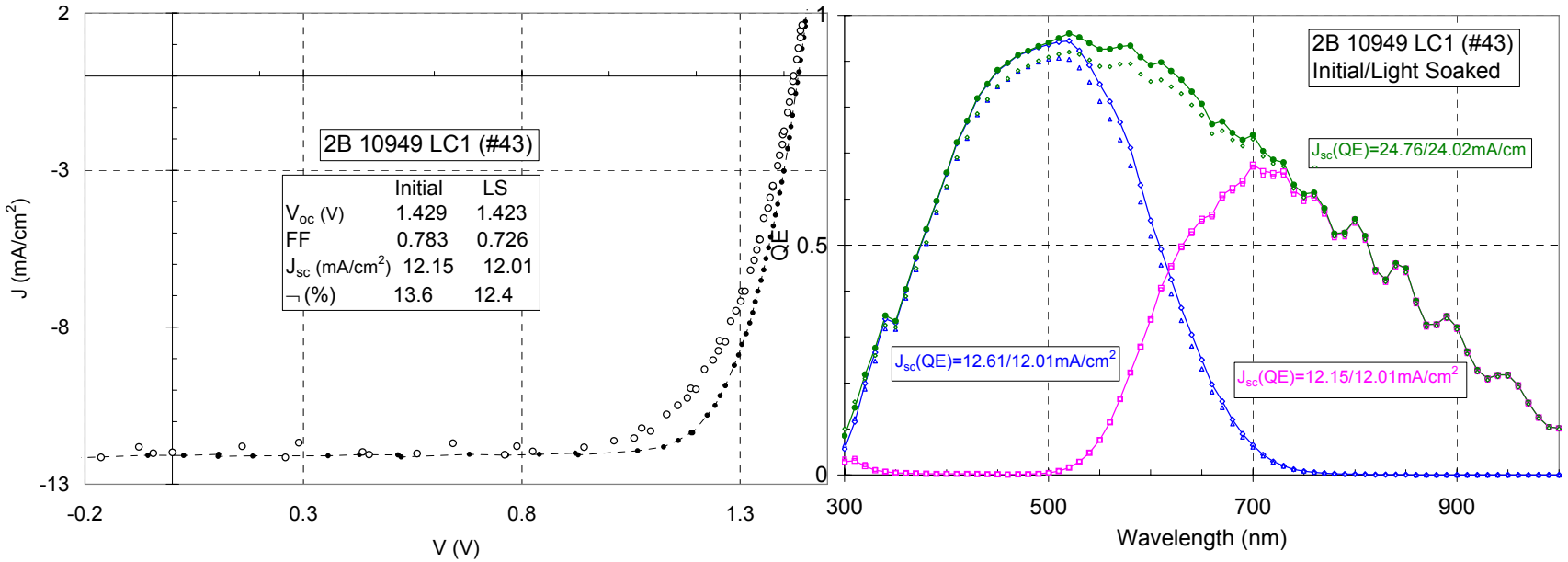
## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells

| No. | Status | $V_{oc}$ (V) | FF | Q (mA/cm²) | | | $J_{sc}$ (mA/cm²) | $P_{max}$ (mW/cm²) |
|---|---|---|---|---|---|---|---|---|
| | | | | Top | Bottom | Total | | |
| 13528 | Initial | 1.445 | 0.755 | 12.00 | 12.17 | 24.17 | 12.00 | 13.1 |
| | Stable | 1.410 | 0.690 | 11.54 | 12.20 | 23.74 | 11.54 | 11.2 |
| 13536 | Initial | 1.444 | 0.741 | 12.28 | 12.21 | 24.49 | 12.12 | 13.0 |
| | Stable | 1.409 | 0.672 | 11.82 | 12.21 | 24.03 | 11.82 | 11.2 |
| 13580 | Initial | 1.454 | 0.750 | 12.67 | 11.68 | 24.35 | 11.68 | 12.7 |
| | Stable | 1.422 | 0.699 | 12.27 | 11.72 | 23.99 | 11.72 | 11.6 |
| 13586 | Initial | 1.440 | 0.737 | 12.46 | 12.13 | 24.59 | 12.13 | 12.9 |
| | Stable | 1.406 | 0.674 | 12.19 | 12.04 | 24.23 | 12.04 | 11.4 |

**a-Si:H/nc-Si:H double junction solar cells, where the deposition times of the top and bottom cell intrinsic layers are 7 and 30 minutes, respectively.**

# • Major Accomplishments-Continue

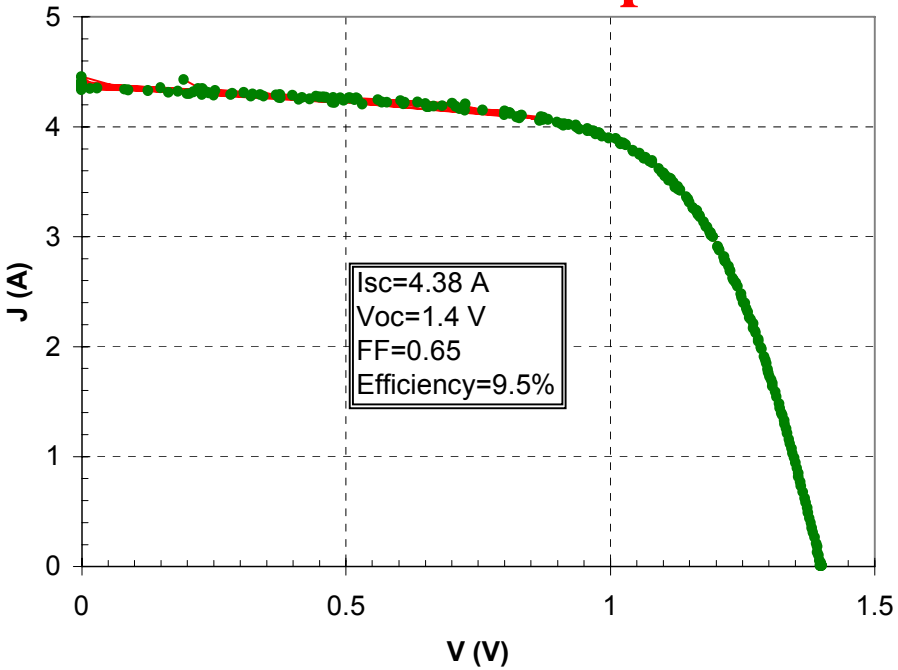
## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells




**A double junction solar cell with a 50 minute deposition time in the bottom intrinsic layer. The total-area stabilized (0.268 cm$^2$) efficiency is 11.6% - lower deposition rate improves efficiency.**

- # Major Accomplishments-Continue

## nc-Si:H as Narrow Gap Intrinsic Layer in Multi-Junction Cells




**Double junction a-Si:H/nc-Si:H modules (~ 420 cm$^2$) with a 50 minute bottom i layer deposition time. The stabilized module efficiency is 9.5%.**

# Schedule of Major Events/Milestones

- **Summarize major events/milestones**

  - The best a-Si:H/a-SiGe:H/a-SiGe:H module efficiency achieved is 8.6%, which is a good start for Phase II milestone efficiency of 9.3%.
  - High rate nc-Si:H solar cells were made with 30 minutes of i layer deposition time. The best total-area (0.268 $cm^2$) cell efficiency is 7.62%, which surpasses Phase II efficiency milestone of 7.0%.
  - High rate nc-Si:H solar cells were made with 60 minutes of i layer deposition time. The best total-area (0.268 $cm^2$) cell efficiency is 7.96%, which matches Phase III milestone efficiency of 8.0%.
  - The best stabilized active-area (0.25 $cm^2$) cell efficiency of 13.3% was achieved with an a-Si:H/a-SiGe:H/nc-Si:H triple-junction structure, which corresponds to a total-area (0.268 $cm^2$) cell efficiency of 12.4%. This is close to the Phase I milestone efficiency of 12.5%.
  - The stabilized module efficiency of 9.5% was achieved using an a-Si:H/nc-Si:H double-junction structure, which is smaller than the Phase I milestone efficiency of 10.5%. Uniformity and higher deposition rate issues are being addressed.

# Future Directions

- **Outline broad future plans**

- We shall continue the research tasks based on the Phase II Plan.
- We shall continue to optimize the a-Si:H and a-SiGe:H deposition parameters for improving the material quality. The target is to achieve 9.3% module efficiency for the Phase II milestone.
- We shall continue the optimization of high rate MVHF deposition of a-Si:H and a-SiGe:H solar cells. The main focus will be on the optimization of a-SiGe:H quality at high rate. Issues with large-area deposition will be addressed.
- We shall focus on the optimization of nc-Si:H solar cells and address the high efficiency, high deposition rate, and large-area deposition issues. The major task is to evaluate the feasibility of using nc-Si:H in the manufacturing lines.