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FY08 Final Report on Photovoltaic Solar Cell Research at BAE/ARL

by Patrick Folkes, Parvez Uppal, and Paul Moffitt

ARL-TR-4845 **June 2009**

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FY08 Final Report on Photovoltaic Solar Cell Research at BAE/ARL

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2009

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
FY08

4. TITLE AND SUBTITLE
FY08 Final Report on Photovoltaic Solar Cell Research at BAE/ARL

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Patrick Folkes, Parvez Uppal, and Paul Moffitt

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-SE-EI
2800 Powder Mill Road
Adelphi MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-4845

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report describes a research initiative in photovoltaic solar cells that was funded by the Power and Energy Division, and established over the past year in the Electro-Optics & Photonics Division in collaboration with BAE Systems. In this report, we summarize the FY08 accomplishments, problems encountered, and plans for future work in this area. We report work on the design, fabrication, and testing of gallium arsenide (GaAs)-based single p-n junction solar cells. The report outlines ongoing technology transfer from BAE systems, relevant FY08 publications and acquisitions, and interactions with U.S. Army Research Laboratory (ARL) personnel, the Communications Electronics Research and Development Engineering Center (CERDEC), the Natick Soldier Center, and the University of Delaware throughout the year.

15. SUBJECT TERMS
Semiconductor

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	UU	24

19a. NAME OF RESPONSIBLE PERSON
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19b. TELEPHONE NUMBER (*Include area code*)
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Summary

Over the past year, a research initiative in photovoltaic solar cells, which was funded by the Power and Energy Division, was established in the Electro-Optics & Photonics Division in collaboration with BAE Systems. In this report, we summarize the FY08 accomplishments, problems encountered, and plans for future work in this area. Gallium arsenide (GaAs)-based single p-n junction solar cell wafers were designed and grown at BAE Systems using a molecular-beam-epitaxy (MBE) growth technique. A nine-level photolithographic maskset, which was designed and developed at BAE Systems, was used to fabricate solar cells. Measurements of the solar cell performance show that some solar cells exhibit reasonably good characteristics, but the as-grown structures have a high defect density, which degraded the performance of the solar cells. The report outlines ongoing technology transfer from BAE systems, relevant FY08 publications and acquisitions, as well as interactions with U.S. Army Research Laboratory (ARL) personnel, Communications Electronics Research and Development Engineering Center (CERDEC), Natick Soldier Center, and the University of Delaware throughout the year.

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1. FY08 Accomplishments

Gallium arsenide (GaAs)-based single p-n junction solar cell wafers were designed and grown at BAE Systems using a molecular-beam-epitaxy (MBE) growth technique. The solar cells were grown on a GaAs substrate and consist of the following semiconductor layers: 1000 Å undoped GaAs; a 2000 Å aluminum/gallium arsenide (AlGaAs) etch-stop layer; 15000 Å n-type GaAs with 8×10^{16} cm^{-3} Silicon doping; 2000 Å p-type AlGaAs with 5×10^{18} cm^{-3} beryllium (Be) doping; and a 100 Å GaAs cap layer with 5×10^{18} cm^{-3} Be doping. A commercial computer program was used to simulate the solar cell performance characteristics. Details of the semiconductor parameters, the assumptions used in modeling the solar cell, and the device operating conditions used in the simulation are given below.

Base substrate was a 3-in semi-insulating GaAs wafer. Growth was in a Gen II Varian MBE machine. The layer structure for growth and simulation was as follows:

Top layer

Thickness: 0.2 µm

Material from $Al_{.3}$ $Ga_{.7}As$.mat

Carrier mobilities from internal model

Dielectric constant: 12.24

Band gap: 1.817 eV

Intrinsic concentration at 300 K: 1754/cm

Refractive index: 3.81

Absorption coefficient from internal model

No free carrier absorption

P-type background doping: 5×10^{18} cm^{-3}

No front diffusion

No rear diffusion

Bulk recombination: $\tau n = \tau p = 7.208$ µs

Front-surface recombination: S model, $Sn = Sp = 1 \times 10^{6}$ cm/s

Rear-surface recombination: S model, $Sn = Sp = 1 \times 10^{5}$ cm/s

N-layer

Thickness: 1.5 μm

Material from GaAs.mat

Carrier mobilities from internal model

Dielectric constant: 13.18

Band gap: 1.424 eV

Intrinsic concentration at 300 K: 2.59×10^{6} cm^{-3}

Refractive index: 3.66

Absorption coefficient from internal model

Free carrier absorption enabled

N-type background doping: 8×10^{16} cm^{-3}

No front diffusion

No rear diffusion

Bulk recombination: $\tau n = \tau p = 7.208$ μs

No Front-surface recombination

No Rear-surface recombination

Etch stop/growth initiation layer

Thickness: 0.2 μm

Material from Al_3Ga_7as.mat

Carrier mobilities from internal model

Dielectric constant: 12.24

Band gap: 1.817 eV

Intrinsic conc. at 300 K: 1754 cm^{-3}

Refractive index: 3.81

Absorption coefficient from internal model

No free carrier absorption

N-type background doping: 8×10^{17} cm^{-3}

No front diffusion

No rear diffusion

Bulk recombination: τn = τp = 7.208 μs

No Front-surface recombination

No Rear-surface recombination

Excitation conditions

Excitation modified from one-sun.exc

Excitation mode: Transient, 200 timesteps

Temperature: 25 ºC

Base circuit: Sweep from –1.1 to 1.2 V

Collector circuit: Zero

Primary light source enabled

Constant intensity: 0.1 W cm^{-2}

Spectrum from am15 g.spc

Secondary light source disabled

The predicted current-voltage characteristic and response predicted by the computer simulation are shown in the figure 1.

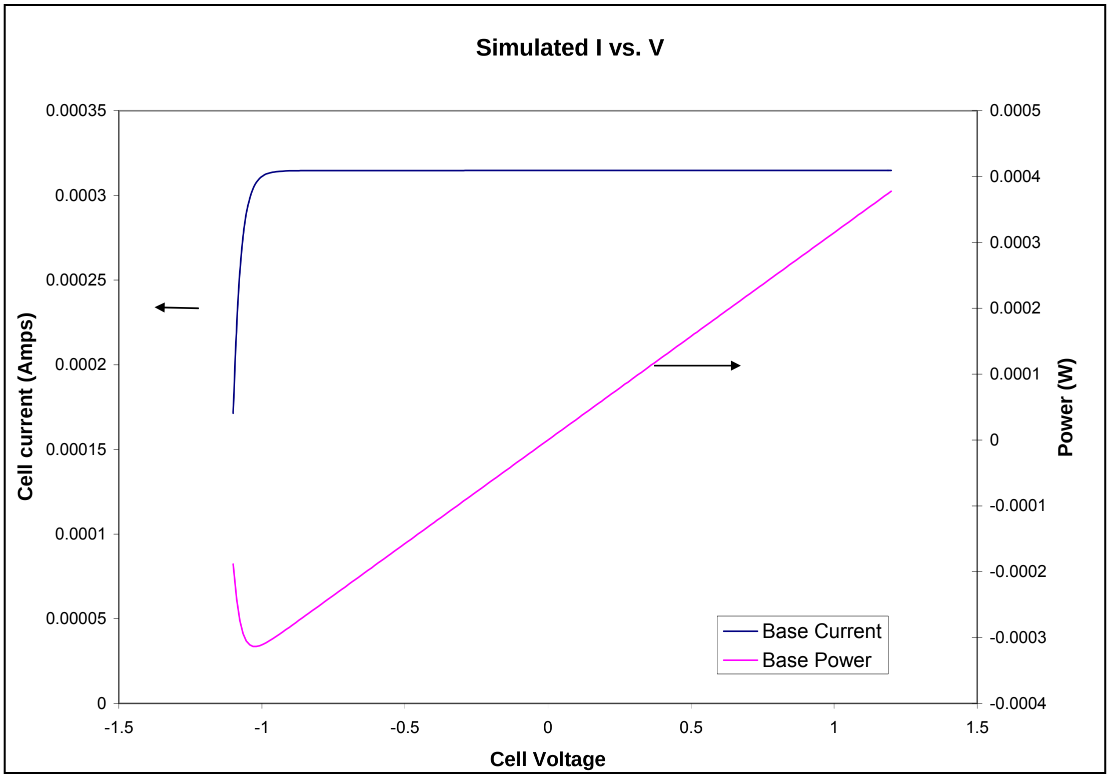


Figure 1. Simulated solar cell characteristics.

The predicted response and current-voltage characteristic is for a 1 mm^2 size solar cell. Simulation was done through PC1D using the layer structure detailed previously. The short-circuit current obtained is 3.148×10^{-4} A and the maximum output power is 3.137×10^{-4} W.

Two wafers were initially grown with this structure. One was processed into solar cells at BAE Systems, and the other was sent to the U.S. Army Research Laboratory (ARL), but was unfortunately lost in shipment. A third wafer has been grown and will be sent to ARL to replace the lost wafer. An additional wafer was grown without the p-type heterostructure, using p-type GaAs in place of the p-type AlGaAs layer.

A nine-level photolithographic maskset was designed and developed at BAE to fabricate solar cells. The fabrication process involves nine separate photolithography steps. A detailed description of the standard fabrication process is given in figures 5 to 9 Hybridization followed our standard process. After dicing the processed wafer into the appropriate size, we hybridized the fanout and solar cell using a Suss FC-150. After hybridization, epoxy was wicked into the space between the wafers. The GaAs substrate was removed following our standard process of lapping followed by dry etching.

Initial testing before hybridization was done on a probe station at BAE Systems. We found that all the larger cells were shorted, indicating a large number of defects in the material. This is most likely because the MBE machine was near the end of a long growth campaign, and particle density was approaching the usable limit. The completion of fanout processing facilitated further testing of the completed solar cells. The fanout used for two different solar cell configurations is shown in figures 2 and 3.

After completion of fanout processing at BAE Systems, samples containing individual 1 mm^2 solar cells and sets of five 4 mm^2 solar cells connected in series were sent to ARL for testing using a solar simulator light source. The solar cells were tested using a constant wave simulator solar light intensity of 100 mW cm^{-2}. Several sets of five series-connected solar cells showed reasonably good characteristics (figure 4), such as a combined open-circuit voltage V_{oc} as high as 3.8 V, a short-circuit current $I_{sc,}$ of 0.61 mA, and a current-voltage fill factor of 61%. Assuming that the V_{oc} for each of the five solar cells is the same, we determine that the single 4 mm^2 solar cell V_{oc} = 0.76 V and the corresponding solar cell conversion efficiency = 7.1%. The non-ideal fanout configuration results in an approximate 30% reduction in the illuminated area and the observed conversion efficiency of the solar cell. Most likely, the relatively low observed conversion efficiency can be primarily attributed to the high density of defects in the semiconductor materials. The individual 1 mm^2 solar cells exhibited V_{oc} = 0.88 V, current-voltage fill factor = 70%, but surprisingly very low I_{sc} = 0.06 mA, and a solar cell conversion efficiency = 4.0%. If we assume that some single 1 mm^2 solar cells exhibit short-circuit current densities as high as the series-connected solar cells (15.25 mA cm^{-2}), then these solar cells would have a conversion efficiency of 9.6%.

BAE Systems is currently working on improvements in the fanout architecture and fabrication process to reduce shielding of the active cell area by the fanout wires and to improve the overall flexibility of the hybridized solar cells. BAE Systems transferred a complete set of photolithography masks including the fanout masks to the Electro-optic Materials Branch at ARL, and plans to continue the transfer of improvements of the fanout process to ARL.

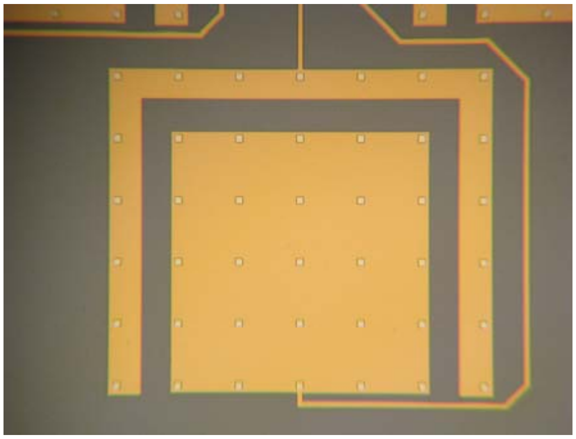


Figure 2. Photograph of fanout complete with indium bumps for a 1 mm^2 individual cell.

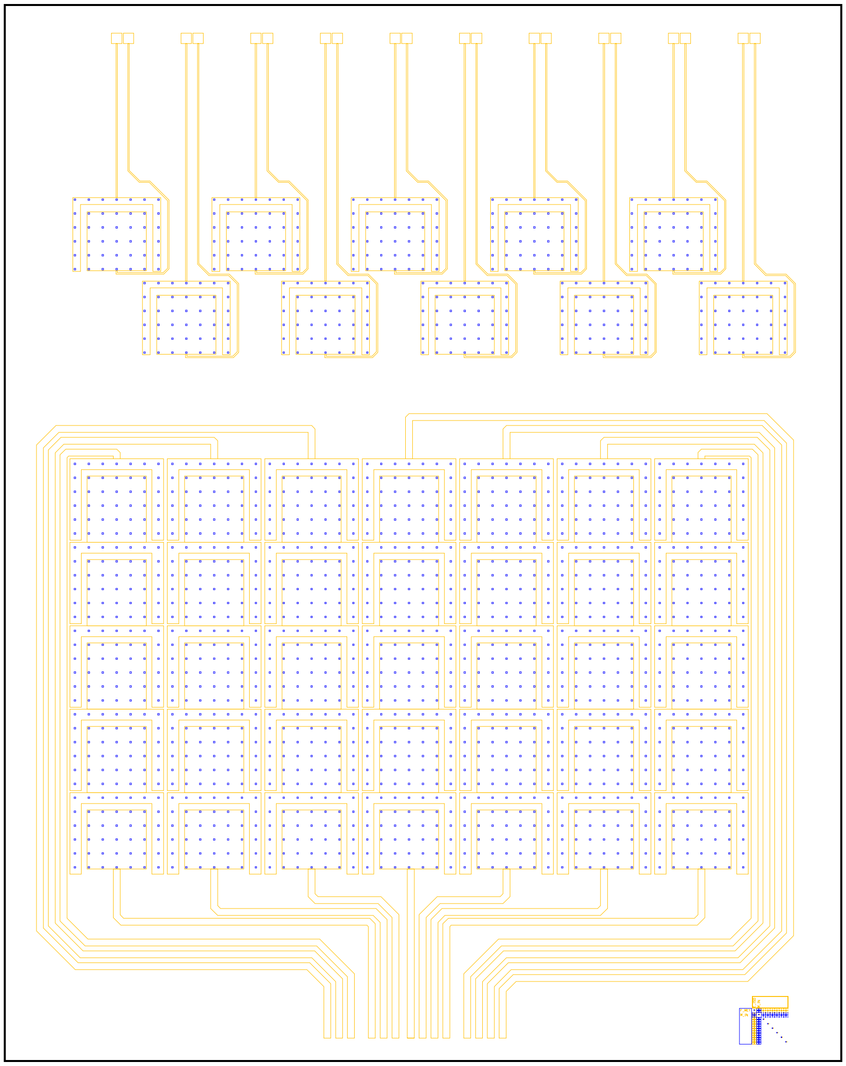


Figure 3. Layout of fanout for 1 mm^2 individual and 5 in a series section of wafer.

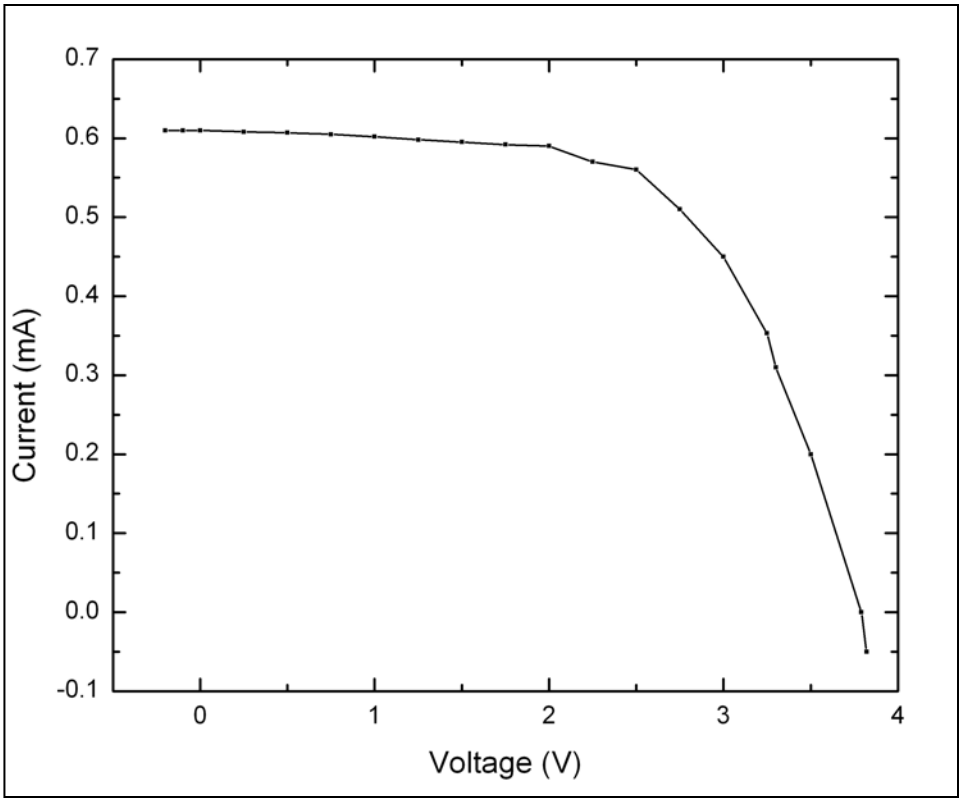
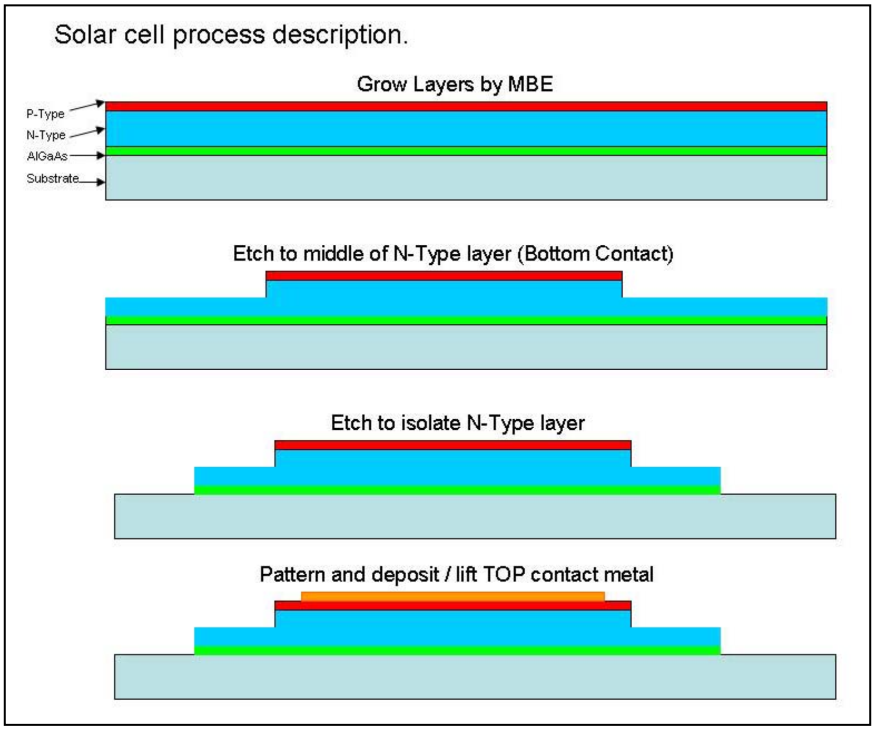


Figure 4. Current-voltage characteristics of series-connected solar cells.



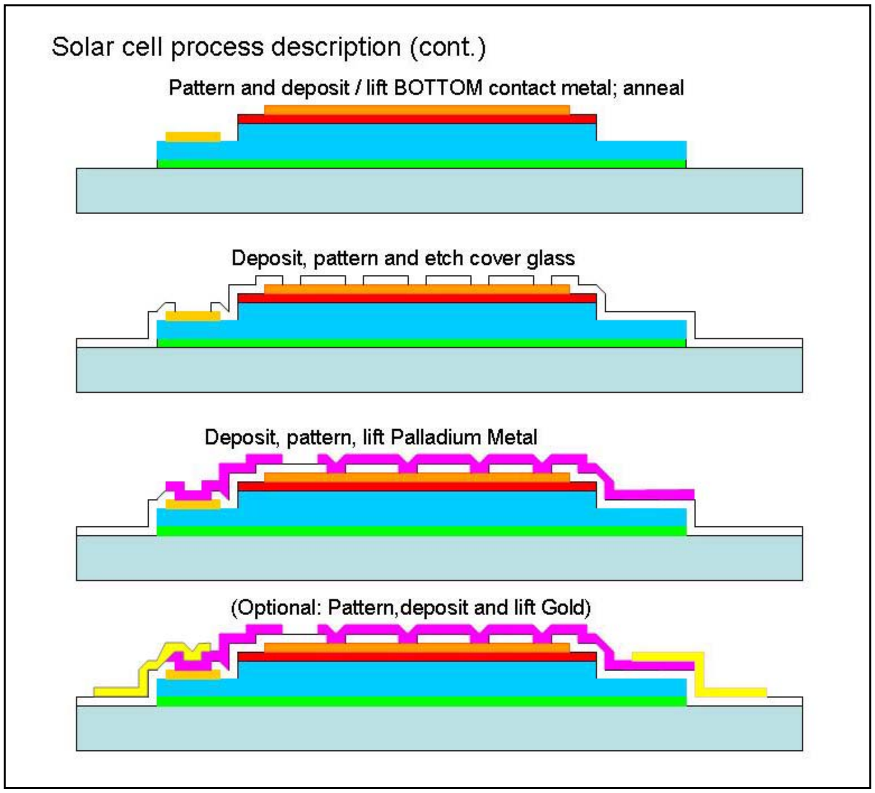
Solar cell process description.

Grow Layers by MBE

Etch to middle of N-Type layer (Bottom Contact)

Etch to isolate N-Type layer

Pattern and deposit / lift TOP contact metal



Solar cell process description (cont.)

Pattern and deposit / lift BOTTOM contact metal; anneal

Deposit, pattern and etch cover glass

Deposit, pattern, lift Palladium Metal

(Optional: Pattern,deposit and lift Gold)

Figure 5. Solar cell process description.

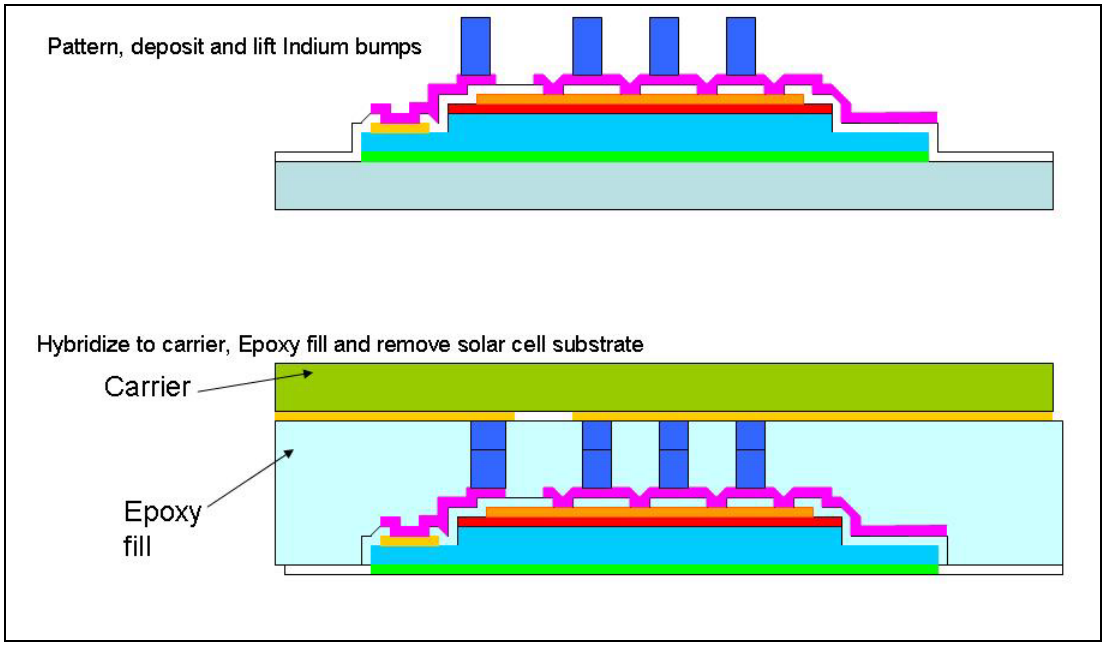
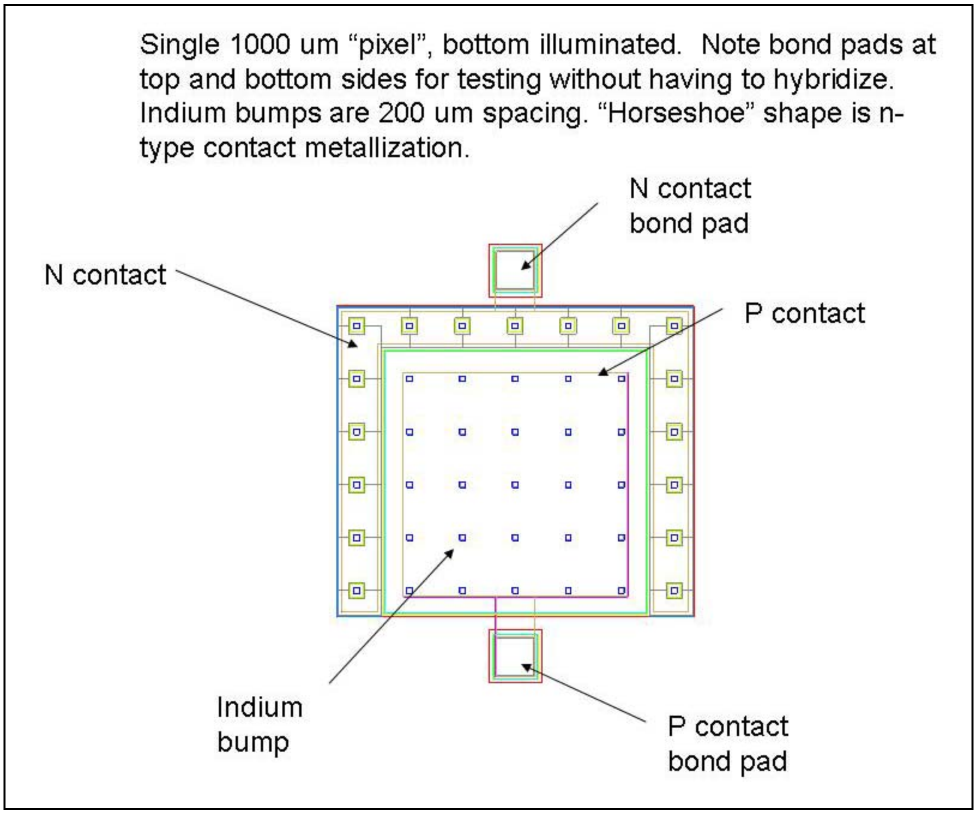


Figure 6. Solar cell hybridized to carrier.



Single 1000 um "pixel", bottom illuminated. Note bond pads at top and bottom sides for testing without having to hybridize. Indium bumps are 200 um spacing. "Horseshoe" shape is n-type contact metallization.

Figure 7. Single 1 cm^2 pixel, bottom illuminated.

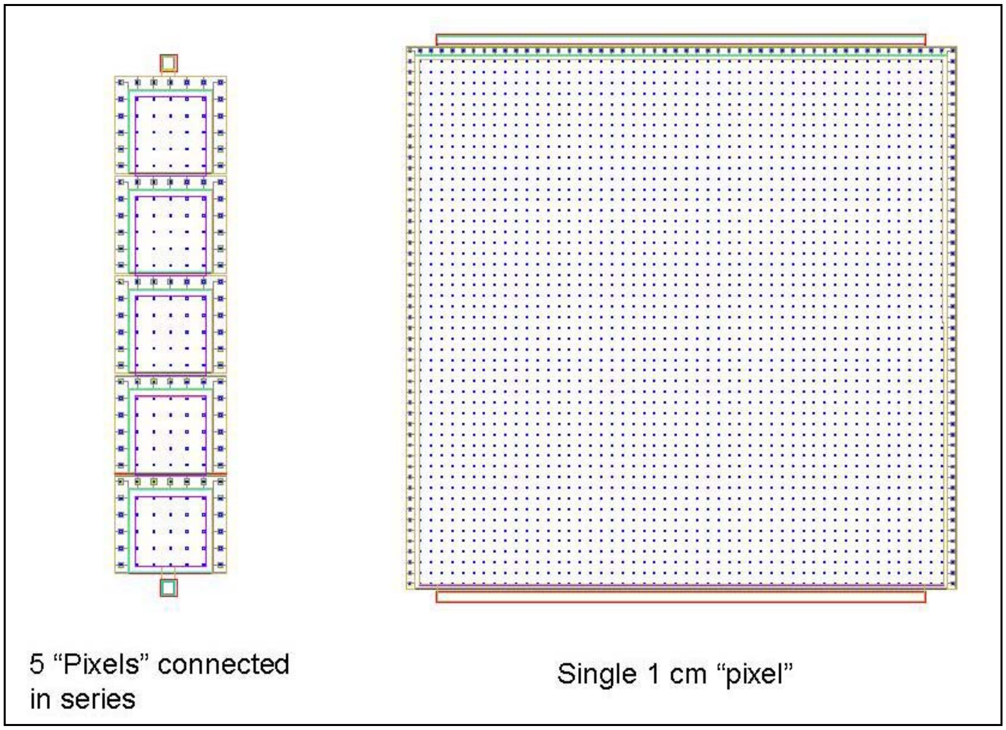


Figure 8. Single and series-connected pixels.

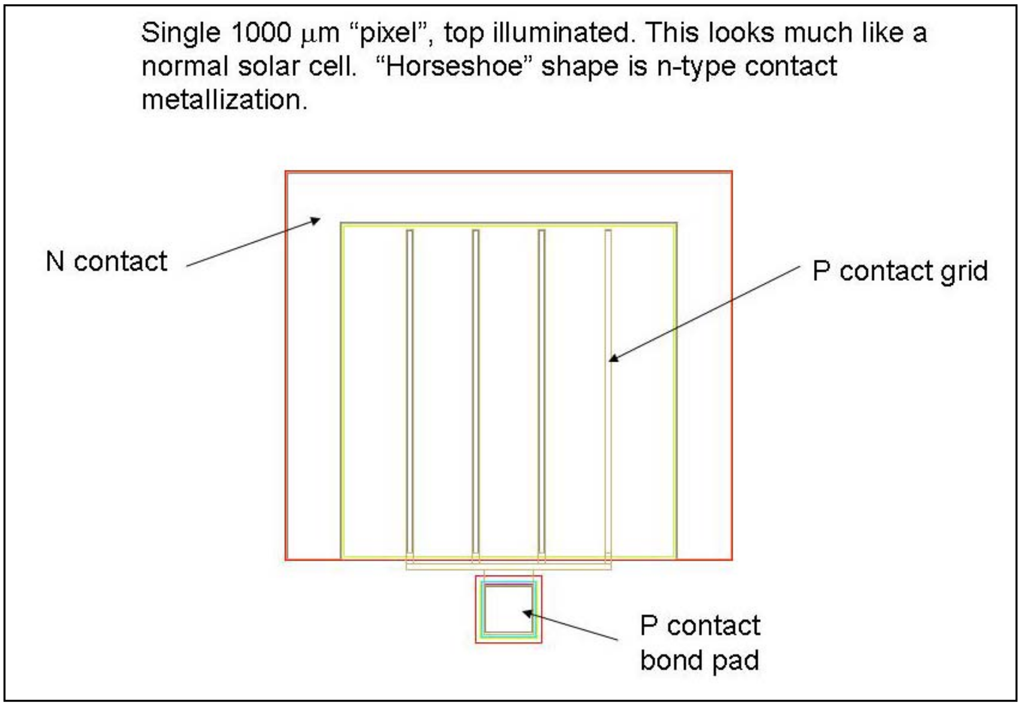


Figure 9. Single 1 cm^2 pixel, top illuminated.

An Oriel Arc Lamp Illuminator coupled to an Apex monochromator and an air mass filter was purchased. The system has the capability to function as a solar simulator (AM1.5), as well as measure the spectral response of solar cells. I am in the final stages of setting up this characterization equipment and a current-voltage measurement system.

A set of three structures for the research on high-efficiency GaAs-based solar cells was designed. We negotiated and signed a mutual non-disclosure agreement between ARL and EpiWorks, the semiconductor foundry that was selected to provide these wafers. After several delays in getting approval for a sole source acquisition for these epitaxial wafers, EpiWorks was awarded the purchase contract to grow the epitaxial structures on 25 September 2008, and the actual contract date for the acquisition was early December. We received the structures in February 2009. These structures will be used for FY09 solar cell research.

GaAs p-n junction wafers designed and grown by BAE Systems were processed to fabricate solar cells samples. After the completion of fanout processing at BAE Systems, samples containing individual 1 mm^2 solar cells and sets of five 4 mm^2 solar cells connected in series were sent to ARL for testing using a solar simulator light source. The solar cells were tested using a constant wave simulator solar light intensity of 100 mW cm^{-2}. Several sets of five series-connected solar cells showed reasonably good characteristics, such as a combined open-circuit voltage V_{oc} as high as 3.8 V, a short-circuit current I_{sc} of 0.61 mA, and a current-voltage fill factor of 61%. Assuming that the V_{oc} for each of the five solar cells is the same, we determine that the single 4 mm^2 solar cell V_{oc} = 0.76 V and the corresponding solar cell conversion efficiency = 7.1%. The non-ideal fanout configuration results in an approximate 30% reduction in the illuminated area and the observed conversion efficiency of the solar cell. Most likely, the relatively low observed conversion efficiency can be primarily attributed to the high density of defects in the semiconductor materials. The individual 1 mm^2 solar cells exhibited V_{oc} = 0.88 V, current-voltage fill factor = 70%, but a surprisingly low I_{sc} = 0.06 mA and a solar cell conversion efficiency = 4.0%. If we assume that some single 1 mm^2 solar cells exhibited short-circuit current densities as high as the series-connected solar cells (15.25 mA cm^{-2}), then these solar cells would have a conversion efficiency of 9.6%.

BAE Systems is currently working on improvements in the fanout architecture and fabrication process to reduce shielding of the active cell area by the fanout wires and to improve the overall flexibility of the hybridized solar cells. BAE Systems has transferred a complete set of photolithography masks, including the fanout masks to the Electro-optic Materials Branch at ARL, and plans to continue the transfer improvements of the fanout process to ARL. In the future, we plan to fabricate and test these solar cells at ARL.

A FY09 Director's Research Initiative (DRI) entitled "Novel High-efficiency Photovoltaic Solar Cells for Micro-robotic Devices," which emphasized the possibility of future collaboration with a Power & Energy Strategic Technology Initiative (STI) on power management, was submitted. In consultation with Dr. Bayne (Power & Energy STI Chair), a presentation about a potential new FY09 Power and Energy STI was given to Dr. Chabalowski, Dr. Weiss, Dr. Lee, Dr. Liu, and Dr. Winner on 7 November 2008. This led to the submission of a new Power and Energy STI proposal entitled “High-Efficiency Photovoltaic Solar Cells for Microsystems” on 12 December 2008.

We reviewed proposals for CERDEC’s Alternative Energy Congressional, actively participated in several Power & Energy Division meetings and workshops, (including some where CERDEC, ARDEC, and Natick Soldier Center participated), and provided feedback to requests for technical reviews and information on solar cell research. We also made contacts with potential collaborators and customers such as CERDEC, Natick, and the University of Delaware. Arrangements for ARL personnel to visit the University of Delaware were made resulting in a productive visit by ARL personnel and possible collaboration/interaction with faculty and students.

I completed data analysis and revised a manuscript that was recently published. The research results reported in this manuscript are relevant to research on solar cells.

Publication: Folkes, P.; Liu, Y. Photocurrent-induced Changes in the Excitonic Photoluminescence from a Single Heterojunction Quantum Well. *Physical Review B* **2008**, *78*, 193304.

Another manuscript “Photocurrent-Induced Transport of Exciton Energy in the Presence of a Two-Dimensional Electron Gas” will be submitted for journal publication.

2. Conclusions

Over the past year a research initiative in photovoltaic solar cells, which was funded by the Power and Energy Division, was established in the Electro-Optics & Photonics Division in collaboration with BAE Systems. GaAs-based single p-n junction solar cell wafers were designed and grown at BAE Systems using a MBE growth technique. A nine-level photolithographic maskset, which was designed and developed at BAE Systems, was used to fabricate solar cells. Measurements of the solar cell performance show that some solar cells exhibit reasonably good characteristics, but the as-grown structures have a high defect density, which degraded the performance of the solar cells.

List of Symbols, Acronyms, and Abbreviations

AlGaAs	aluminum/gallium arsenide
ARL	U.S. Army Research Laboratory
Be	beryllium
CERDEC	Communications Electronics Research and Development Engineering Center
DRI	Director's Research Initiative
GaAs	gallium arsenide
MBE	molecular beam epitaxy
STI	Strategic Technology Initiative

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