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Innovation for Our Energy Future

Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates

Final Technical Report
15 September 2004 – 30 September 2006

S.A. Ringel
Ohio State University
Columbus, Ohio

Subcontract Report
NREL/SR-520-44250
November 2008

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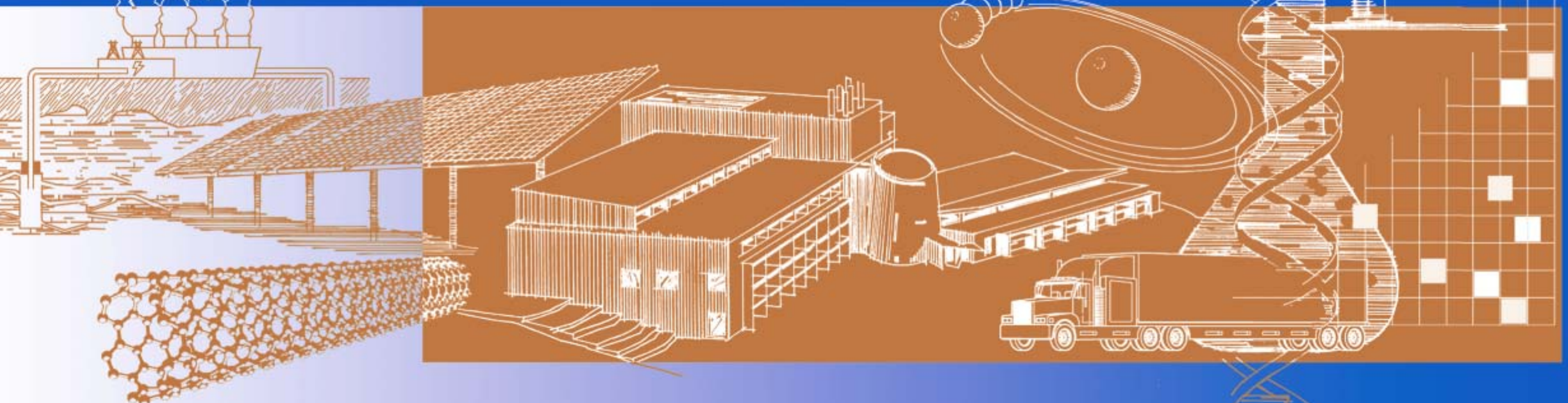

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Executive Summary Project

This research program aimed to develop ultra-efficient III-V multijunction concentrator solar cells on *patterned SiGe/Si and Ge substrates* that are capable of 40+% efficiency under high solar concentration. The approach couples compositionally graded buffers with reduced-area III-V epitaxy on patterned substrates to achieve an ultra-low dislocation density condition for achieving maximum efficiency from several types of small-area, multijunction concentrator cell designs. For InGaP/InGaAs metamorphic multijunction cells with near-optimal bandgap profiles (~1.7-1.8 eV/1.1-1.2 eV), reduced-area epitaxy on patterned substrates will enhance dislocation filtering well beyond what has been achieved on planar substrates to date, while simultaneously defining small concentrator cell areas that are desired for high concentration ratios and to minimize the consequences of flux nonuniformity. The project was to include reduced-area epitaxy on patterned Ge substrates and also on SiGe/Si substrates, exploiting our experience in achieving high-quality virtual SiGe substrates, upon which reduced-area III-V solar cell epitaxy can be performed. For these substrates, the presence of SiGe provides a realistic solution for achieving optimal three-junction bandgap profiles at close to lattice-matched conditions by incorporating an 0.9-eV bandgap SiGe bottom cell underneath a conventional, lattice-matched InGaP/GaAs (1.9 eV/1.4 eV) dual junction. Moreover, the substitution of Si for Ge for high-concentration conditions is advantageous from the viewpoint of thermal conductivity. Ultimately, the goal for the program is to demonstrate a realistic path to achieve III-V multijunction concentrator efficiencies in excess of 40% through a substrate-engineering approach that combines compositional grading with patterned epitaxy suitable for small-area cells designed for high concentration.

Project History and Relationships

This project continued a recently completed (12/31/04) NREL subcontract *ACQ-1-36019-06 - "III-V Solar Cells on Si Substrates Using SiGe Buffer Layers,"* which was funded under the NREL program Photovoltaic Technologies Beyond the Horizon. Briefly, the goal for that project was fundamental in nature, to explore and solve materials science issues leading toward the development of the first multijunction, high-efficiency III-V compound solar cells on Si using SiGe interlayers. The expectation was that if the fundamental efforts were successful, then this would lead to a III-V cell technology development based on the use of SiGe engineered substrates. Indeed, the project resulted in breakthrough results that largely led to the development of this current program. Of the many findings reported in 18 journal and conference papers, 9 invited talks, and 1 PhD dissertation generated via that $150K/yr program, several notable accomplishments were: (1) achieving the world's first epitaxial III-V dual-junction solar cells grown on Si using the promising SiGe buffer technology and voltage output in excess of 2 volts on Si; (2) the first spectrum-optimized metamorphic InGaP/InGaAs 1.7-eV/1.1-eV cell on SiGe; (3) demonstrating >18% efficient single-junction GaAs/Si solar cells using SiGe, with active-area efficiency in excess of 20%; and (4) demonstration that p+n polarity Ill-V cells will substantially outperform n+p configured cells in the presence of a low dislocation density, which is the first demonstration that the optimization of high-efficiency metamorphic III-V solar cell design must account for how dislocations preferentially impact one carrier type over another. A full account of the progress made in the previous project can be found in its Final Report. This project was designed to build directly on the materials science knowledge and guidelines developed in that program leading toward concentrator cell applications. Several activities at the close of that project, in particular the continued optimization of the dual junction (DJ) on SiGe via advances in our InGaP material to improve current collection from this cell as well as the dislocation-device polarity relationship, crossed over from one program to the next, as these fed directly into the goals of this program.

Summary of Activities and Status

Good progress was made in the first phase of this subcontract, as detailed in the FY05 annual technical report. The successfully achieved milestones for Phase I were in addition to continuation of our advances in the development of lattice-matched InGaP/GaAs DJ grown on Ge/SiGe/Si and also the development of metamorphic InGaP/InGaAs (1.7/1.1 eV) cells grown on Ge/SiGe/Si that carried over from the prior NREL subcontract. *Unfortunately, at the close of Phase I, the subcontract with OSU was terminated, though an additional $35K was gratefully received from NREL by January 2006 (original budget for Phase II was $149K) to allow the student supported by the project (Matthew Lueck) to complete his studies by March 2006 in a truncated, 3-month Phase II effort. As a result, the tasks and milestones originally designated for this subcontract were reduced/eliminated commensurate with the reduced, and subsequently eliminated, funding.*

This first year (Phase I) of this program focused on three tasks:

Task 1: Patterning Ge wafers
Task 2: Growth of highly doped SiGe relaxed buffers on Si by UHVCVD
Task 3: Growth and fabrication of lattice-mismatched, metamorphic 1.15-1.25-eV bandgap InGaAs cells on patterned Ge substrates.

The second year (Phase II) of this program was truncated to ~25% of its total funding and duration. Therefore, focus was reduced to the following shortened task list:

Task 4: Growth of highly doped SiGe relaxed buffers on Si (cont. of Task 2)
Task 9: Growth of GaAs on 94% Ge SiGe buffers
Task 10: Growth of metamorphic InGaP/InGaAs cell structures on Ge.

Please note that the task numbering corresponds to the initial SOW and that specifics of tasks 9 and 10 are reduced in scope form the initial SOW due to funding and time reduction. Tasks 5, 6, 7, 8 and 10 along with all of Phase III were eliminated in their entirety.

The status of each task is measured by the state of the respective milestone, as follows (*denotes modified milestone):

M-1.1 Patterned Ge substrates

We have developed several mask sets and a robust, chemical etch process that enables us to generate patterned Ge substrates with mesa dimensions ranging from 10 um to 1 cm, in various geometric arrangements with respect to wafer offcut based on new masks designed in the project.

M-1.2. Low TD n+ SiGe planar buffers on Si

We have reduced the threading dislocation density (TDD) in high-Ge (96%-100%) Ge to -6x10^5 cm^{-2}. Modeling shows that this 30%-40% reduction in TDD will result in minority-carrier lifetimes in p and n devices being equivalent to those in GaAs/GaAs devices. We have also increased the uniform n-type doping in these buffers well into the 10^{17} cm^{-3} range, thus mitigating a potential source for series resistance in subsequent concentrator cells.

M-1.3. InGaAs cell on patterned Ge

We have grown a variety of lattice-mismatched InGaAs layers and step-graded buffers designed to support the 1.2-eV-bandgap bottom cell of the optimized metamorphic DJ cell to determine the efficacy of dislocation filtering as a function of grading parameters and strain. Evidence for enhanced dislocation filtering was obtained by counting dislocation etch pits as a function of mesa size and orientation, and we are continuing to optimize this process. The first 1.2-eV-bandgap InGaAs solar cells on patterned Ge wafers were grown and processed; initial cell measurements are now under way.

M-2. 1. Patterned SiGe/Si

We have successfully transitioned our substrate patterning process from Ge (milestone M-1.1.) to SiGe/Si, achieving the same set of pattern dimensions in various geometric arrangements with respect to wafer offcut direction.

*M-2.2. * Metamorphic InGaP/InGaAs cell on planar Ge and SiGe*

We have successfully grown an 1.7-eV InGaP on 1.15-eV InGaAs internally lattice matched DJ solar cell on both Ge and virtual Ge (on Si) substrates. We have observed a positive impact on reducing thermally induced microcracking on SiGe compared to lattice-matched InGaP/GaAs growth on the same substrates in very preliminary studies.

The following sections provide some more detail of the actual research involved with the various milestones achieved and tasks performed.

Technical Approach

All III-V/Ge MBE growth was carried out at OSU on graded-composition SiGe/Si substrates having terminal compositions of 90%-100% Ge. The SiGe substrates were obtained via subcontract to our long-term collaborator, Prof. Gene Fitzgerald of MIT. III-V growth using MOCVD was performed at the MOCVD facilities at NASA Glenn Research Center via an existing Space Act Agreement between OSU and NASA GRC (D. Wilt). Additionally, OSU performed extensive structural (SEM, EBIC, TEM, XRD, etch pit density) characterization, electrical characterization (I-V/T, DLTS, CV, Hall, etc.), optical characterization (PL) and cell testing (QE, Light I-V). Time-resolved PL studies for lifetime measurements were performed in collaboration with NREL (R. Ahrenkiel). Test devices and solar cells were processed at OSU and were tested at OSU and NREL. In cases where AR coatings were used, the NASA GRC facilities were accessed.

The MBE growths were performed using a 3-inch modular Gen-II system that had been dedicated for arsenide/phosphide growth. Standard effusion cells were used for all group III elements; valved cracker sources were used for the group V elements (As_2 and P_2); and a low-flux, low-temperature source was used for initial Ge epitaxy on cleaned SiGe substrates. The MOCVD growths were performed in a home-built horizontal flow MOCVD system, and the SiGe was grown using either LP-CVD or UHVCVD. SiGe wafer diameters ranged from 4 to 8 inches and were diced or cleaved to fit into the 3-inch III-V growth systems. The qualities of SiGe substrates (relaxation, threading dislocation density, etc.) were characterized using high-resolution XRD, plan view TEM, and etch pit density measurements. Relaxed, virtual Ge wafers typically had threading dislocation densities of 1-4x106 $^{CM-2}$ in this study, as measured by plan view TEM.

Key Program Results

Even though the subcontract was terminated after Phase I plus a small fraction for the Phase II component, important progress was made and findings obtained partly as a result of the leverage via other funded programs and the carryover inertia from the prior NREL project. This report summarizes several of the more pertinent results along with a list of publications and demographic information. Complete details can be found in the appendices, via complete copies of publications receiving support from this program.

1. Improved dual-junction, lattice-matched InGaP/GaAs, metamorphic InGaP/InGaAs cells on Si and electronic properties of defects in III-V photovoltaics grown on SiGe

The continuation of subcontract *ACQ-1-36019-06* into the initial phase of this subcontract resulted in the first reported epitaxial III-V dual junction solar cells grown on Si using SiGe buffers and the first metamorphic III-V dual-junction cells on Si. A major goal for this program was to build upon the extensive materials results of the prior program and the initial, promising device results obtained there. Here, we focused on optimizing the InGaP and A1GaInP layers with respect to improved top cells for multijunctions on SiGe, as well as optimization of thin tunnel junctions and accommodating the complex growth temperature profiles required for growing the III-V DJ cells by MBE. The ultimate goal was the demonstration of fully processed and functioning prototype III-V DJ cells on Si with current matching. We also grew and tested the first "metamorphic" InGaP/InGaAs 1.6/1.1-eV tandem cells grown on Si and conducted extensive studies of traps in these unique, metamorphic PV structures. Key highlights of this work included:

- The first demonstration of > 2V 1-sun Voc on Si using an epitaxial III-V cell.
- The preservation of dislocation and APD control for DJ structures on Si.
- Demonstration that DJ performance on SiGe is not limited by fundamental lattice-mismatch issues, and that the 1^{st} generation prototype performance is current-limited by the InGaP cell.
- Demonstration of 3x improvement in MBE InGaP top cell current collection via annealing.
- Current-matched performance was achieved with high performance by applying the annealing step to the dual-junction cell on SiGe.
- First spectrum optimized metamorphic InGaP/InGaAs 1.6/1.1-eV cell on SiGe.
- Elimination of microcracking by compressive strain overshoot for metamorphic cells on Si.
- Proof that no additional traps are introduced by epitaxial growth of both InGaP and GaAs on SiGe/Si substrates, compared to growth on GaAs and Ge substrates, via DLTS studies

2. Preferred device polarity for metamorphic III-V and III-V/Si solar cells

This again was continued from subcontract *ACQ-1-36019-06.* We performed extensive experimental studies and theoretical analyses of how residual densities of threading dislocations differentially impact carrier recombination in n- and p-type GaAs. We found a clear device polarity preference for GaAs and InGaP/GaAs solar cells in the presence of a small but non-negligible density of dislocations, with p+n configured devices being much less sensitive to dislocation-mediated recombination. This is the first demonstration that the optimization of high-efficiency metamorphic III-V solar cell design must account for how dislocations preferentially impact one carrier type over another. Key findings include:

- Demonstration that minority-carrier holes in n-type GaAs display substantially higher lifetimes than do minority-carrier electrons in p-type GaAs for all dislocation densities above 10^5 cm^{-2}.
- Explanation for lower electron lifetime on the basis of their higher mobility and thus greater sampling frequency of residual dislocations as compared with holes in GaAs.
- Demonstration that GaAs diodes with p+n polarity yield higher built-in voltages than n+p diodes for dislocation densities greater than 10^5 cm^{-2}, which is attributed to lower depletion-region recombination currents resulting from longer hole lifetimes in the n-type base for the former.
- Model that explains that the polarity preference for diodes (and solar cells) depends on (1) whether depletion-region recombination dominates the diode leakage current, and, in that case, (2) whether holes and electrons have different mobility values. Built-in voltages will always be higher in cases where the higher lifetime carrier is the minority carrier in the base region of the diode.

- Experimental proof of the polarity-preference effect for both GaAs and InGaP metamorphic diodes and solar cells, with InGaP cells being less sensitive to the presence of dislocations than GaAs cells due to a reduced disparity in carrier mobilties for InGaP.
- Theoretical work that showed InGaP/GaAs DJ cells to have a higher tolerance to dislocation density than single-junction GaAs cells.

3. Advances in SiGe substrates for PV applications: reduced dislocation density, higher doping, and $Si_{0.04}Ge_{0.96}$ substrates

A breakthrough in reducing threading dislocation density (TDD) in relaxed Ge layers on Si has been demonstrated by working to optimize the higher Ge-content region of our unique SiGe grading process. TDD values in relaxed Ge on Si have been reduced from our previous record low of ~$1x10^6$ cm^{-2} to a new value of ~ $6x10^5$ cm^{-2}. We have explored the fundamental dependence of TDD evolution on several factors, particularly the initial substrate offcut magnitude and also the growth temperature used in the final 4% of the graded layer. With this knowledge, we can now "dial in" an arbitrary surface lattice constant with extremely low TDD values, including those needed to support a SiGe subcell with a 0.9-eV bandgap. This has led us to grow APD-free, low-TDD GaAs directly on 96% Ge SiGe substrates for the first time. Although further study is needed, no obvious problems are apparent by initiating and growing GaAs on this mixed alloy surface, an important first step to creating high-efficiency cells based on lattice constants slightly smaller than GaAs. These findings are significant. According to our models of Voc and carrier lifetime dependence upon TDD that have accurately guided our work to date, reducing the TDD from ~$1\text{-}2x10^6$ cm^{-2} to ~$5\text{-}6x10^5$ cm^{-2} will enable Ill-V carrier lifetimes on Si to *match* that obtained via homoepitaxy, thereby expanding diffusion lengths and decreasing recombination losses to unprecedented levels such that performance levels of III-V cells on planar SiGe should closely match cells on Ge substrates for each cell parameter. Secondly, we believe that at this new low TDD value, n+p configured devices should perform equally well as p+n configured devices, thus enabling consistency with conventional technology. Finally, this demonstrates the path to achieve III-V epitaxy on lattice-engineered, mixed SiGe composition substrates, opening the door for integrating an optimized 0.9-eV subcell monolithically underneath a high-efficiency Ill-V MJ cell for the first time.

4. Metamorphic 1.2-eV-bandgap InGaAs subcell on planar and patterned Ge wafers

Lattice-mismatched InGaAs solar cells having a bandgap of 1.2 eV were designed, grown, and fabricated on both planar and pre-patterned Ge substrates. EQE measurements demonstrated that strong carrier collection right up to the bandedge was achieved for the metamorphic 1.2-eV cell, in spite of the aggressive grade used to obtain this lower bandgap. Devices were successfully developed on both types of substrates. Had this program continued, this cell would have been a bottom subcell for the complete metamorphic InGaP/InGaAs DJ cell on patterned substrates. This finding is significant for several reasons: (1) The successful demonstration that high-quality InGaAs materials with the appropriate bandgap required for subsequent super-efficient, metamorphic InGaP/InGaAs cells can be achieved on both planar and patterned Ge substrates enables the next step, which is the integration of an internally lattice-matched InGaP top cell to achieve the desired 1.7/1.2-eV bandgap profile; (2) This also shows that 3-D engineered substrates are of great promise as a general means to integrate high-performance solar cells with arbitrary substrates.

5. III-V lattice-matched epitaxy on $Si_{0.o4}Ge_{0.ss}$ virtual substrates

A goal of this program is to utilize the SiGe alloy to generate a virtual substrate with a tunable lattice constant, in order to provide a lattice-matched surface for epitaxy of unique Ill-V PV multijunctions with ideal bandgap profiles. As described above, we focused on developing SiGe with terminal Ge compositions of 100% (our "conventional" virtual Ge substrate) and on Ge compositions from 90% to 96%. These would provide a Si-based substrate that could support lattice-matched GaAsP-InGaAsP double junctions that would in turn be paired with an epitaxial SiGe subcell with a bandgap of 0.80.95 eV that is integrated by virtue of doping the upper part of the SiGe graded buffer. While we were not able to reach the final goal due to the abrupt termination of the subcontract, we indeed successfully grew GaAs that is perfectly lattice matched to 96% Ge SiGe virtual substrates, as reported in the 2005 Technical Annual Report.

List of Papers Submitted or Published, and Presentations that Received Either Full or Partial NREL Support or Directly Impacted this Subcontract

<u>Manuscripts published (or pending to appear) in peer-reviewed journals:</u>

- P.E. Smith, M. Lueck, S.A. Ringel, and L.J. Brillson, *"Atomic Diffusion and Interface Electronic Structure at $In_{0.49}Ga_{0.s,}P$/GaAs Heterojunctions,"* submitted, J. Vac. Sci. Technol. B (2006).
- P.E. Smith, M. Lueck, S.A. Ringel, and L.J. Brillson, *"Atomic Diffusion and Electronic Structure in $Al_{0.52}Ga_{0.48}P$/GaAs Heterostructures,"* submitted, J. Vac. Sci. Technol. B (2006).
- M. Gonzalez, C.L. Andre, R.J. Walters, S.R. Messenger, J.H. Warner, J.R. Lorentzen, A.J. Pitera, E.A. Fitzgerald. and S.A. Ringel, *"Deep level defects in proton radiated GaAs grown on metamorphic SiGe/Si substrates," J.* Appl. Phys. 100, 034503:1-7 (2006).
- M. Lueck, C.L. Andre, A.J. Pitera, M.L. Lee, E.A. Fitzgerald, and S.A. Ringel, *"Dual Junction InGaP/GaAs Solar Cells Grown on Metamorphic SiGe Substrates," IEEE Electron Devices Letters 27, 142-144 (2006).*
- O. Kwon, J.J. Boeckl, M.L. Lee, A.J. Pitera, E.A. Fitzgerald and S.A. Ringel, *"Monolithic integration of AIGaInP laser diodes on SiGe/Si substrates by molecular beam epitaxy," J.* Appl. Phys. 100, 013103:1-7 (2006).
- C.L. Andre, D.M. Wilt, A.J. Pitera, M.L. Lee, E.A. Fitzgerald, and S.A. Ringel, *"Impact of Dislocation Densities on n+p and p+n Junction GaAs Diodes and Solar Cells on SiGe Virtual Substrates,"* J. Appl. Phys. 98, pp. 014502: 1-5(2005).
- O. Kwon, Y. Lin, J.J. Boeckl, and S.A. Ringel, *"Properties of digitally-alloyed A1GaInP grown by solid source molecular beam epitaxy," J.* Electron. Mater. 34, pp. 1-6 (2005).
- C.L. Andre, J.A. Carlin, J.J. Boeckl, D.M. Wilt, M.A. Smith, A.J. Pitera, M.L. Lee, E.A. Fitzgerald, and S.A. Ringel, *"Investigations of high performance GaAs solar cells grown on Ge-SiGe-Si substrates,"* IEEE Trans. El. Dev. 52, pp. 1055-1060 (2005).

<u>Papers published in non-peer-reviewed journals or in conference proceedings:</u>

- J.A. Carlin, C.L. Andre, O. Kwon, M. Gonzalez, M. Lueck, E.A. Fitzgerald, D. Wilt. and S.A. Ringel, *"III- V device integration on Si via metamorphic SiGe substrates,"* Electrochemical Society Transactions, vol. 3 number 7, SiGe and Ge: Materials, Processing and Devices 729-743 (2006). **Invited.**
- D. Wilt, S.A.Ringel, E.A. Fitzgerald, P. Jenkins, and R. Walters, *"Preliminary on-orbit performance data from GaAs on Si solar cells aboard MISSE-5,"* Proc. 4th World Conf. On Photovoltaic Energy Conversion (WCPEC-4), Hawaii (2006).

- S.A. Ringel, M. Lueck, C.L. Andre, D.M. Wilt, E.A. Fitzgerald, and D. Scheiman, *"Toward a III-V Multijunction Space Cell Technology on Si," P*roc. 19th Space Photovoltaic Research and Technology Conf. (Cleveland), 2005.
- M. Gonzalez, C.L. Andre, R.J. Walters, S.R. Messenger, J.H. Warner, J.R. Lorentzen, D. M. Wilt, E.A.Fitzgerald, and S.A. Ringel, *"Radiation Study of GaAs Solar Cells Grown on Ge/SixGel-x/Si Substrates," P*roc. 20"' European Photovoltaic Solar Energy Conference and Exhibition, Barcelona, Spain (2005).
- S.A. Ringel, C.L. Andre, E.A. Fitzgerald, A.J. Pitera, and D.M. Wilt, *"Multi-Junction III-V Photovoltaics on Lattice-Engineered Si Substrates,"* Proc. IEEE Photovoltaic Specialists Conf. (Orlando), (2005).
- M. Lueck, M. Gonzalez, O. Kwon, C. Andre and S.A. Ringel, *"Impact of Annealing and V.-III Ratio on Properties of MBE Grown Wide Bandgap AIGaInP Materials and Solar Cells," P*roc. IEEE Photovoltaic Specialists Conf. (Orlando) (2005).
- D.M. Wilt, A.T. Pal, N.R. Prokop, S.A. Ringel, C.L. Andre, M.A. Smith, D.A. Scheiman, P.P. Jenkins, W.F. Maurer, B. McElroy, and E.A. Fitzgerald, *"Thermal Cycle Testing of GaAs on SI and Metamorphic Tandem on Si Solar Cells,"* Proc. IEEE Photovoltaic Specialists Conf, Orlando (2005).
- S.A. Ringel, C.L.Andre, M. Lueck, D. Isaacson, A.J. Pitera, E.A. Fitzgerald and D.M. Wilt, *"III-V Multi-Junction Materials and Solar Cells on Engineered SiGe/Si Substrates,"* Proc. Mater. Res. Soc. Symp., Boston, (2005).

Papers presented at meeting but not published in conference proceedings:

- S.A. Ringel, *"Metamorphic III- V/Si photovoltaics for terrestrial and space power,"* Key Conference 2006, San Antonio (2006). **Invited.**
- S.A. Ringel, O. Kwon. M. Lueck, J. Boeckl, and E.A. Fitzgerald, *"III-V/Si device integration via metamorphic SiGe substrates,"* 3rd International SiGe Technology and Device Meeting, Princeton, NJ (2006). **Invited.**
- M. Gonzalez, A. Armstrong, C.L. Andre, A. Carlin, and S.A. Ringel, *"Optical and electrical defect characterization of InGaP grown on metamorphic SiGe substrates,"* 48th TMS/IEEE Electronic Materials Conf., State College, PA (2006).
- M. Gonzalez, C.L. Andre, R.J. Walters, S.R. Messenger, J.H. Warner, J.R. Lorentzen, D. M. Wilt, E.A. Fitzgerald, and S.A. Ringel, *"Deep Level Defects in GaAs Grown on Metamorphic SiGe Substrates and Evidence for Dislocation-Enhanced Point Defect Gettering,"* 47th IEEE/TMS Electronic Mater. Conf., Santa Barbara, CA 2005.
- SA. Ringel, *"Defect Engineering in III-V/Si Integration and Applications for Optoelectronics and Photovoltaics,"* International Conference on Materials for Advanced Technologies (ICMAT), Singapore (2005).
- O. Kwon, A. J. Pitera, M. L. Lee, E. A. Fitzgerald, and S. A. Ringel, *"Room temperature operation of A1GaInP laser diodes monolithically integrated on metamorphic SiGe/Si substrates,"* International Conference on Materials for Advanced Technologies (ICMAT), Singapore (2005).

Other notable presentations related to NREL project (not including- domestic university colloquia):

- S.A. Ringel, *`Solar Energy Technology: Research, Development and Commercialization,"* National University of Singapore and Singapore-MIT Alliance (SMA) **invited** lecturer, February, 2005.
- S.A. Ringel, *"Heterogeneous Integration for High Performance, Low-Cost Solar Cells,"* University Colloquium, Shanghai Jiaotong University, Shanghai, China, March 2005. **Invited.**
- S.A. Ringel, *"Nanomaterials in Emerging Semiconductor Device Technologies,"* Nano-Applications Summit, Cleveland, OH (2005). **Invited.**

Contract Demographics and Personnel Information

Personnel receiving full or partial financial support during part or all of this agreement:

- **P.I.:** Professor Steven A. Ringel
- **Graduate Students:**
  Mr. Andrew Carlin, PhD Candidate
  Ms. Kathie Dykes, MS Candidate
  Ms. Maria Gonzalez, PhD Candidate
  Mr. Matt Lueck, MS Candidate

Demographic Data for Life of This Agreement:

Fully and partially NREL-supported students at Ohio State since 2001

Name	Degree/yr	Position
Carrie Andre	MS 2001; PhD, 2004	Research Engineer, Akzo Nobel
John Carlin	MS, 1999; PhD, 2001	Research Scientist, AFRL
Ms. Kathie Dykes	MS, 2007	PhD student (MIT)
Mr. Ryan Clark	MS, 2003	Consultant, Private
Ms. Maria Gonzalez	MS, 2003	PhD Candidate at OSU
Dr. Mantu Hudait	Postdoc, 2006	Research Engineer, Intel
Dr. Ojin Kwon	PhD, 2005	Research Engineeer, Lumileds
Mr. Matt Lueck	MS, 4/06	Staff Engineer, Research Triangle
Dr. Yong Lin	PhD, 2007	Asst. Professor, Michigan Tech Univ.

Awards for NREL-supported students during agreement

Kathie Dykes

- NSF PhD Fellow
- OSU University Fellow

Andrew Carlin

- NASA Graduate Student Researcher Program Fellow

Awards/Distinctions for Steven A. Ringel during agreement

- Named the Neal. A. Smith Endowed Chair in Electrical Engineering
- Elected to Fellow of AAAS
- Named Director of OSU Institute for Materials Research.

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14. ABSTRACT *(Maximum 200 Words)*
This research program aimed to develop ultra-efficient III-V multijunction concentrator solar cells on *patterned SiGe/Si and Ge substrates* that are capable of 40+% efficiency under high solar concentration. The approach couples compositionally graded buffers with reduced-area III-V epitaxy on patterned substrates to achieve an ultra-low dislocation density condition for achieving maximum efficiency from several types of small-area, multijunction concentrator cell designs. For InGaP/InGaAs metamorphic multijunction cells with near-optimal bandgap profiles (~1.7-1.8 eV/1.1-1.2 eV), reduced-area epitaxy on patterned substrates will enhance dislocation filtering well beyond what has been achieved on planar substrates to date, while simultaneously defining small concentrator cell areas that are desired for high concentration ratios and to minimize the consequences of flux nonuniformity. The project was to include reduced-area epitaxy on patterned Ge substrates and also on SiGe/Si substrates, exploiting our experience in achieving high-quality virtual SiGe substrates, upon which reduced-area III-V solar cell epitaxy can be performed. For these substrates, the presence of SiGe provides a realistic solution for achieving optimal three-junction bandgap profiles at close to lattice-matched conditions by incorporating an 0.9-eV bandgap SiGe bottom cell underneath a conventional, lattice-matched InGaP/GaAs (1.9 eV/1.4 eV) dual junction. Moreover, the substitution of Si for Ge for high-concentration conditions is advantageous from the viewpoint of thermal conductivity.

15. SUBJECT TERMS
PV; III-V multijunction concentrator; solar cells;Ge subtrate; lattice match; dual junction; thermal conductivity; patterned Si:Ge/Si; compositional grading; InGaP/InGaAs; small area;

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