RICHARD R. KING

School of Electrical, Computer and Energy Engineering
Arizona State University
551 E. Tyler Mall, Engineering Research Center, Rm. 177 tel: (480) 727-3698
P.O. Box 875706 fax: (480) 965-8058
Tempe, AZ 85287-5706 email: richard.r.king@asu.edu

EDUCATION

Stanford University	Electrical Engineering	Ph.D., 1990
Stanford University	Electrical Engineering	M.S., 1987
Stanford University	Physics	B.S., 1985

with Distinction, with Departmental Honors, Phi Beta Kappa

RESEARCH INTERESTS

Semiconductor materials and solid-state device physics; defects and recombination activity in semiconductors; materials and electronic device characterization; high-efficiency III-V multijunction solar cells; thermodynamic limits of photovoltaic conversion; photon recycling enhancement in photovoltaic devices operating near theoretical efficiency limits; hybrid III-V and group-IV semiconductor devices; interface passivation and defect tolerance in semiconductors; recombination at heterovalent semiconductor interfaces; carrier-selective contacts; universal patterns in defect energy level formation among broad families of semiconductors; physical mechanisms causing anomalously low minority-carrier recombination activity at grain boundaries and other crystal defects in certain semiconductors; effects of surface and interface defect energies on electronic and photonic devices using nanostructured features dominated by their high surface to volume ratio; metamorphic, lattice-mismatched (Al)GaInP and (Al)GaInAs semiconductor materials and their use in high-efficiency solar cells; dilute nitride GaInNAsSb lattice matched to GaAs and Ge, and dilute nitride GaNPAs and GaInNP semiconductors lattice matched to Si; low-cost, flat-plate tandem solar cells and modules; very-high-throughput methods of compound semiconductor growth; transparent interconnection and passivation layers for multijunction solar cells; energy production averaging of grid-connected photovoltaic systems across broad geographic regions; and integration of photovoltaic systems into living spaces, buildings, and urban planning.

SELECTION OF SIGNIFICANT IMPACT RESEARCH AND INNOVATION ACTIVITIES

Arizona State University, School of Electrical, Computer and Energy Engineering, 2015-present, Professor

- Investigating thermodynamic efficiency limits of solar cells, and the physics of photon recycling, light management, and wavelength and angle selectivity at surfaces in high-efficiency photovoltaic devices.
- Investigating phenomenon of defect tolerance in compound semiconductors such as $Cu(Ga,In)Se_2$, GaInN, InP, $CH_3NH_3PbI_3$, and connections to energy level formation and atomic configuration patterns across semiconductor families.
- Researching novel methods and materials for III-V and II-VI interface recombination passivation, and connections to bulk defect tolerant behavior.
- Exploring recombination and current transport characteristics of carrier-selective contacts for high-efficiency, low-cost silicon solar cells.

- Developing characterization principles and techniques for separating surface and bulk recombination, and determining impurity bonding configuration, band bending, and defect energy distribution in low-cost thin-film solar cell materials such as polycrystalline GaInP, InP, CdSeTe and (Ag,Cu)(In,Ga)Se_2 .
- Investigating 1.6-2.0 eV semiconductor materials that can be grown an order of magnitude more rapidly than conventional growth for low-cost, flat-plate tandem solar cells, *e.g.*, on silicon bottom cells.
- Developing low-cost, flat-plate tandem cell structure and optically transparent subcell interconnect layers, *e.g.*, for monolithic (Mg,Zn)CdTe top cells on silicon.
- Setting research strategy in the fundamentals for high-efficiency photovoltaics (PV), tandem solar cell integration, and terawatt scale PV branches of the Quantum Energy and Sustainable Solar Technologies (QESST) NSF-DOE Engineering Research Center, as its Research Director.
- Planning multiple-center framework for continuing the collaborative, self-sustaining research models established in QESST beyond the 10 year life of the present center, vertically integrated from fundamental materials investigations, to photovoltaic device research, to large fielded projects and societal considerations of widespread generation of solar electricity.

Spectrolab, Inc., Division of Boeing Co., 1997-2015, Principal Scientist and Technical Fellow, Photovoltaic Cell R&D

- Experimental studies of recombination activity at defects in metamorphic (Al)GaInP and (Al)GaInAs grown by metal-organic vapor-phase epitaxy (MOVPE) with lattice mismatch from 0.2% to 3.5%, and contributions to knowledge on defect mitigation in metamorphic materials leading to high-efficiency multijunction solar cells built from these materials.
- Achieved first solar cell of any kind to reach over 40% efficiency in 2006, with 40.7%-efficient metamorphic GaInP/ GaInAs/ Ge 3-junction terrestrial concentrator solar cell.
- Achieved record 41.6% efficiency lattice-matched 3-junction solar cell in 2009 and 41.6% efficiency metamorphic 3-junction cell in 2010.
- Championed long series of record solar cell efficiencies 2001-2010, from 35 to >41%, resulting in the emergence of III-V multijunction cells as the photovoltaic technology with the highest and most rapidly rising efficiency, and leading directly to the conversion from silicon to III-V multijunction cells in nearly all commercial high-concentration photovoltaic (HCPV) systems.
- Led the high-efficiency concentrator solar cell research teams recognized for this work by Scientific American 50 and R&D 100 Awards for Spectrolab and the National Renewable Energy Laboratory (NREL), in 2001, 2002, and 2007.
- Developed first 3-junction GaInP/ GaInAs/ Ge metamorphic solar cells in 2000, for both space and terrestrial concentrator applications, with an active germanium bottom cell in combination with metamorphic GaInP and GaInAs cells.
- Developed wide-bandgap transparent tunnel junctions with peak tunneling currents in excess of 35,000 suns equivalent.
- Demonstrated the first space solar cells with >30% efficiency under the AM0 solar spectrum.
- Led the externally and internally funded research teams at Spectrolab that developed device structure innovations leading directly to the last 3 generations of space solar cells, and to future generations with >37% target AM0 efficiency.
- Studied composition-graded buffer structure to accommodate lattice mismatch in III-V devices: effect of metal-organic vapor phase epitaxy (MOVPE) conditions on residual strain, propagation of defects, minority-carrier lifetime, and metamorphic device performance.

- Showed that bandgap-voltage offset $W_{oc} \equiv (E_g/q) - V_{oc}$ is largely independent of bandgap for a wide range of metamorphic and lattice-matched semiconductors from 0.67 to 2.1 eV. Formulated semiconductor device physics equations in terms of bandgap-voltage offset, to give a clearer physical understanding and more general analysis of the multiple subcell bandgaps in multijunction cells. Calculated fundamental E_g dependence of bandgap-voltage offset using Shockley-Queisser detailed balance model, bearing out experimental observations.
- Pioneered novel 4-, 5- and 6-junction solar cell architectures, including designs with metamorphic subcells, and with active ~1-eV GaInNAs subcell. Demonstrated first 6-junction solar cell; open-circuit voltage now >5.3V.
- Growth and characterization of GaInNAs(Sb) and other novel 1.0-1.3 eV semiconductors lattice-matched to GaAs and Ge for high-efficiency multijunction solar cells.
- Developed epitaxially-grown germanium subcells integrated with III-V solar cells, and novel multijunction solar cell designs incorporating Si, SiGe, Ge, and other group-IV subcells.
- Developed novel inverted solar cell growth, wafer bonding and substrate removal approaches, to form high-efficiency multijunction solar cells with new bandgap combinations, including integration of different III-V subcells, and integration of III-V cells with silicon and other solar cell materials.
- Characterized factors causing group-III sublattice disordering and its effect on band structure in lattice-matched and lattice-mismatched GaInP and AlGaInP.
- Experimentally determined the effect of lattice mismatch on interface and bulk recombination in AlGaInP/GaInP/AlGaInP and GaInP/GaInAs/GaInP double heterostructures, measured by time-resolved photoluminescence (TRPL).

Siemens Solar Industries, 1992-1997, Senior Research Scientist

- Developed silicon concentrator solar cells for operation up to 50 suns based on low-cost, one-sun solar cell technology with screen-printed metallization.
- Demonstrated 3-terminal Si solar cells with transistor-like operation, with screen-printed interdigitated back contacts.
- Investigated lattice defects, impurities, minority-carrier recombination in photovoltaic devices.
- Mentored graduate student thesis to characterize activation energy of Fe-B pairing and associated light-induced degradation of minority-carrier lifetime in silicon solar cells.

Georgia Institute of Technology, 1990-1992, Research Eng.

- Characterized minority-carrier recombination in B-diffused layers in Si and Al-doped Si layers formed by epitaxial regrowth.
- Refined contactless photoconductivity decay measurements as a function of excess minority-carrier concentration.
- Expanded high-lifetime processing capabilities of the Georgia Tech Microelectronics Research Center.

Stanford University, Doctoral Research, Electrical Engineering Dept., 1985-1990

- Experimentally determined bandgap narrowing and minority-carrier recombination at the Si/SiO_2 interface as functions of dopant concentration in heavily-doped silicon.
- Developed models for emitter saturation current density J_o with doping-dependent surface recombination velocity in passivated emitters, still used for silicon solar cell design today.

- Designed, built, and characterized early large-area (>35 cm^2) back point-contact silicon solar cells for one-sun, flat-plate applications.
- Demonstrated record one-sun silicon solar cell with 22.3% efficiency and open-circuit voltage over 700 mV (independently confirmed, aperture area, >8 cm^2) in 1988 with back point-contact cell design.
- Theoretical efficiency limits of multijunction photovoltaic cells with varying bandgap and recombination parameters.
- Design of novel heterojunction devices, band structure modeling of SiGe strained layers for Ge-rich compositions.

Stanford University, Undergraduate Research, Physics Dept., 1981-1984

- Modeling of thermophotovoltaic systems with wavelength-selective emissivity.
- Three-dimensional modeling of magnetic field in a magnetic monopole detector predicted to result from a monopole passing through cylindrical, superconducting shield.

PROFESSIONAL AWARDS, RECOGNITIONS, AND HONORS (SELECTED)

- Elected Fellow of the Institute of Electrical and Electronics Engineers (IEEE) – 2017
- William R. Cherry Award – 2010
  for "Outstanding Contributions to Photovoltaic Science and Technology,"
  awarded at the 35th IEEE Photovoltaic Specialists Conference
- Elected IEEE Senior Member – 2008
- Boeing Silver Phantom Award – 2007, 2008
- R&D 100 Award, Spectrolab Team Leader – 2007
- Boeing S&IS World-Class Engineering Award – 2007
- Elected Boeing Technical Fellow – 2006
- Elected Boeing Associate Technical Fellow – 2005
- Inducted into NASA/Space Technology Hall of Fame – 2004
- Scientific American 50 Award, Spectrolab Team Leader – 2002
- R&D 100 Award, Spectrolab Team Leader – 2001
- Boeing Special Invention Awards – 2000, 2002, 2007 (2), 2011
- Hughes and Boeing Technical Excellence Awards – 1998, 1999, 2000, 2002

SELECTION OF SIGNIFICANT PROFESSIONAL AND SCHOLARLY SERVICE ACTIVITIES

1. **Co-Founding Editor**, IEEE Journal of Photovoltaics (J-PV), Served as Co-Founding Editor of the IEEE Journal of Photovoltaics since 2010, before its inaugural issue in July 2011, providing an archival scholarly journal devoted to photovoltaics within the IEEE family of publications.

   In 2014, the journal was awarded an impact factor of 3.0 based on its first 3 years of operation, one of the highest inaugural impact factors ever achieved by an IEEE journal. Present impact factor: 3.075 (1/2018).

2. **Research Director**, NSF-DOE Quantum Energy and Sustainable Solar Technologies (QESST) Engineering Research Center, 2015 – present.

3. **PV Horizons Working Group** – Organization led by National Renewable Energy Laboratory to define photovoltaic research priorities for U.S. policymakers and energy stakeholders, and for scientific community in energy-related fields, 2016 – present.

4. **Management Committee (MC) European Cooperation in Science and Technology (COST) Observer**, for this intergovernmental framework for the creation of research networks, in COST Action PEARL PV, 2019.

5. **Scientific Committee**, European Photovoltaic Solar Energy Conference (EU PVSEC), 2012 – present.

6. **Cherry Committee and Past Chair**, Governing Board of IEEE Photovoltaic Specialists Conference (PVSC), 2011 – present.

7. **Australian PV Strategic Research Initiative** – Organization led by University of New South Wales to promote Australian photovoltaic research collaboration with U.S. and other countries, 2017 – present.

8. **Scientific Advisory Board**, Photonics at Thermodynamic Limits (PTL) Energy Frontier Research Center, Stanford University, Stanford, CA, 2018 – present.

9. **Graduate Faculty in Materials Science**, School for Engineering of Matter, Transport and Energy (SEMTE), Arizona State University, 2016 – present.

10. **Graduate Faculty in Chemistry**, School of Molecular Sciences, Arizona State University, 2016 - present.

11. **Graduate Faculty in Physics**, Arizona State University, 2019

12. **Conference General Chair**, 40th IEEE Photovoltaic Specialists Conference (PVSC), Denver, CO, 2014. The IEEE PVSC is generally recognized as the world's premier conference on the science and technology of solar cells, leading over 100 top scientists in the field on the volunteer Organizing and Program Committees.

    This conference had over 1500 attendees, and over 1100 submitted abstracts, over half of which were submitted from outside the United States making this a highly international conference.

13. **Reviewer**, Proceedings of the National Academy of Sciences, 2019.

14. **Subarea Chair**, III-V Single and Multijunction Solar Cells, 46th IEEE Photovoltaic Specialists Conf., Chicago, Illinois, June 16-21, 2019.

15. **IEEE Photovoltaic Specialists Conference (PVSC) International Committee** – Organization led by PVSC to foster international collaboration in photovoltaics research, and in international scientific conference planning – *7th World Conf. on Photovoltaic Energy Conversion (WCPEC) and 45th IEEE Photovoltaic Specialists Conf.*, Waikoloa, HI, June 10-15, 2018.

16. **WCPEC International Advisory Committee (IAC)** – Organization that is the oversight and steering committee for the World Conferences on Photovoltaic Energy Conversion (WCPEC) – *7th World Conf. on Photovoltaic Energy Conversion (WCPEC) and 45th IEEE Photovoltaic Specialists Conf.*, Waikoloa, HI, June 10-15, 2018.

17. **External Advisory Board**, Light-Material Interactions EFRC, California Institute of Technology, Pasadena, CA, 2012 – 2018.

18. **Co-Organizer**, Materials Research Society (MRS) Spring Meeting, Phoenix, Arizona – 2017

19. **Scientific Advisory Board**, University of California, Santa Barbara (UCSB) Center for Energy Efficient Materials, 2010 – 2014.

20. **Co-Organizer**, Technology Roundtable on Concentrator Photovoltaics, UC Santa Barbara – 2012
21. **Technical Program Chair**, 35th IEEE Photovoltaic Specialists Conf., Honolulu, Hawaii – 2010.
22. **Tutorials Chair**, 33rd IEEE Photovoltaic Specialists Conf., San Diego, California, May 11-16, 2008.
23. **Technical Program Chair**, 4th International Conf. on Solar Concentrators, El Escorial, Spain – 2007.
24. **Area Chair**, 4th World Conf. on Photovoltaic Energy Conversion, Waikoloa, Hawaii, May 7-12, 2006.
25. **Area Chair**, 31st IEEE Photovoltaic Specialists Conf., Lake Buena Vista, Florida, Jan. 3-7, 2005.
26. **Principal investigator**, $15M Air Force Research Laboratory Dual-Use Science and Technology (DUS&T) and Next-Generation Solar Cell (AFRL Next-Gen) programs at Spectrolab, Inc., Division of Boeing Co., which led to the demonstration of the first space solar cells with over 30% AM0 efficiency, and developed the technology needed for the last 3 generations of space solar cells.
27. **Principal investigator**, multi-year $1.7M AFRL R&D program at Spectrolab, Inc., to develop new high-efficiency space solar cell architectures.
28. **Principal investigator,** responsible for high-efficiency terrestrial concentrator cell development for $2.5M High Performance Photovoltaics (HiPerf PV) program at Spectrolab, Inc., from the U. S. Dept. of Energy (DOE) through the National Renewable Energy Laboratory (NREL). This program was key to the development of high-efficiency III-V concentrator cells as the highest efficiency solar cell technology, and the technology that would become dominant in high-concentration photovoltaic (HCPV) systems.
29. Won $13M U. S. Dept. of Energy (DOE) Solar America Initiative program at Spectrolab, Inc., with Boeing team, to research high-efficiency III-V terrestrial concentrator cells, and reduce cost of electricity generated by concentrator photovoltaics.
30. Track record of highest solar cell efficiencies and innovative proposal writing brought in funding of over $30M at Spectrolab, Inc., for multijunction solar cell development.
31. Recruited and mentored team of young top-notch researchers, to form leading research group at Spectrolab on high-efficiency multijunction photovoltaic cells.
32. Team-taught course "Physics and Chemistry of Renewable Energy" with Profs. Harry Atwater, Nathan Lewis, and others, Applied Physics Dept., California Institute of Technology, Spring 2007.
33. Taught tutorial "III-V Semiconductor Materials and Multijunction Solar Cells," at the 4th World Conf. on Photovoltaic Energy Conversion, 2006.
34. Program management and technical guidance for Photovoltaic Manufacturing Technology (PVMaT) program at Siemens Solar Industries, from the U. S. Dept. of Energy (DOE) through NREL.

Ph.D. STUDENTS ADVISED

1. Aymeric Maros, Electrical Engineering, Arizona State University,
   Graduated: May 2017
   Dissertation: *Modeling, Growth, and Characterization of III-V and Dilute Nitride Antimonide Materials and Solar Cells*

2. Chaomin Zhang, Electrical Engineering, Arizona State University, co-advised with Prof. Christiana Honsberg,
   Graduated: Sep. 2017
   Dissertation: *Gallium Phosphide Integrated with Silicon Heterojunction Solar Cells*

3. Abhinav Chikhalkar, Materials Science, Arizona State University, expected graduation date 2020.

4. Madhan Kumar Arulanandam, Electrical Engineering, Arizona State University, expected graduation date 2021.

5. Sean Babcock, Electrical Engineering, Arizona State University, expected graduation date 2021.

6. Christopher Gregory, Materials Science, Arizona State University, expected graduation date 2023.

7. Nicholas Irvin, Physics, Arizona State University, co-advised with Prof. Christiana Honsberg, expected graduation date 2022.

Ph.D. VISITING SCHOLARS

1. Bernice Mae Fetalvero Yu Jeco, University of Tokyo, Visiting Researcher, Oct. 2018 – Jan. 2019, Univ. of Tokyo Advisor: Prof. Yoshitaka Okada.

M.S. STUDENTS ADVISED

1. Kevin Tyler, Arizona State University, graduation date May 2019.

UNDERGRADUATE STUDENTS ADVISED

1. Brandon Nigl, Arizona State University, Electrical Engineering, graduation date May 2019.

2. Kathryn Douglass, Arizona State University, Electrical Engineering, graduation date May 2021.

COURSES TAUGHT

1. Properties of Electronic Materials, EEE 352, undergraduate course, Fall 2019, Arizona State University, Textbooks: *Quantum Dragons*, Brian Skromme; *Semiconductor Physics and Devices, 4th Ed.*, Donald A. Neamen.

2. Solar Cells, EEE 565, graduate course, Spring 2019, Arizona State University, Textbooks: *The Physics of Solar Cells*, Jenny Nelson.

3. Advanced Photovoltaics, EEE 598, graduate course, Fall 2018, Arizona State University, Textbooks: *Physics of Solar Cells (3rd Ed.)*, Peter Würfel and Uli Würfel; *The Materials Science of Semiconductors*, Angus Rockett.
   Preparing this course to be to become a regularly offered course at ASU
   (EEE 570, Advanced Photovoltaics).

4. Properties of Electronic Materials, EEE 352, undergraduate course, Spring 2018, Arizona State University, Textbooks: *Quantum Dragons*, Brian Skromme; *Semiconductor Physics and Devices, 4th Ed.*, Donald A. Neamen.
5. Advanced Photovoltaics, EEE 598, graduate course, Fall 2017, Arizona State University, Textbooks: *Physics of Solar Cells (3rd Ed.)*, Peter Würfel and Uli Würfel; *The Materials Science of Semiconductors*, Angus Rockett.
6. Properties of Electronic Materials, EEE 352, undergraduate course, Spring 2017, Arizona State University, Textbooks: *Quantum Dragons*, Brian Skromme; *Semiconductor Physics and Devices, 4th Ed.*, Donald A. Neamen.
7. Solar Cells, EEE 565, graduate course, Fall 2016, Arizona State University, Textbooks: *The Physics of Solar Cells*, Jenny Nelson.
8. Advanced Photovoltaics, EEE 598, graduate course, Spring 2016, Arizona State University, Textbooks: *Physics of Solar Cells (2nd Ed.)*, Peter Würfel; *The Materials Science of Semiconductors*, Angus Rockett.