Laureates of the National Medal of Science and the National Medal of Technology and Innovation: An ECS "Hall of Fame"

by Krishnan Rajeshwar

Over the years, many ECS members have been recognized for their contributions and accomplishments as scientists and engineers outside of the Society community. Few awards or prizes match the cachet associated with the the National Medal of Science™ and the National Medal of Technology and Innovation™, especially given that these prestigious honors consider the societal impact of a candidate's work. In the words of the National Science & Technology Medals Foundation Executive Director, Robin Rathmann-Noonan, the work must have "saved lives, asked and answered important questions, and helped shape the course of this country and the planet." In this article, we profile some past and recent awardees of the National Medal of Technology and Innovation and the National Medal of Science programs, who are also (or have been) ECS members. Before we do that, the awards themselves are briefly introduced.

ECS Hall of Fame

A list of ECS members who have received the Medals.

National Medal of Science
Alfred Cho (1993)
Norman Hackerman (1993)
Nick Holonyak (1990)
Rudolph Marcus (1989)
Fred Seitz (1973)
Peter Debye (1965)

National Medal of Technology and Innovation
Adam Heller (2007)
C. Grant Willson (2007)
Alfred Cho (2005)
Nick Holonyak (2002)
Jerry Woodall (2001)
Wilson Greatbatch (1990)
Gordon Moore (1990)

The National Medal of Technology and Innovation

This medal (formerly known as the National Medal of Technology) is the highest honor for technological achievement bestowed on American innovators by the President of the United States. To quote from the award brochure, "It celebrates remarkable people whose vision, creativity, and brilliance truly reflect the uniquely American spirit of innovation. This spirit makes it possible for our country to lead the world in scientific discovery and technological development. These American innovators are a wellspring of opportunity, employment, and progress for the entire country. More than that, they also serve as an inspiration to the next generation of innovators, so necessary to America's future." This last statement could not ring truer in the light of recent concerns expressed about the erosion of American leadership in technological prowess and innovation.

Established by Congress in 1980, the President has presented 182 awards to individuals, teams, and companies since 1985. After evaluation by a distinguished committee, recommendations are forwarded to the Secretary of Commerce, who then makes recommendations to the President for a final decision. The United States Patent and Trademark Office is responsible for administering the National Medal of Technology and Innovation program.

The National Medal of Science

This was established in 1959 to honor individuals deserving of special recognition for their outstanding contributions to knowledge in the following fields: physical, biological, mathematical, engineering, social, and behavioral sciences. Again to quote from the award brochure: "The National Medal of Science highlights the benefits bestowed on society by the very best minds in modern science, recognizing their sterling contributions to humanity's wealth of knowledge and spirit of discovery."

An elite committee of 14 scientists and engineers (including two *ex officio* members (the Director of the Office of Science & Technology, and the President of the National Academy of Sciences) is appointed by the President to evaluate the nominees for the Award. Since its inception, the National Medal of Science has been awarded to 442 distinguished scientists and engineers. The National Science Foundation administers this award for the White House.

It is of interest to note that awards have been made posthumously in both cases, a practice departing from, for

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ECS Members Receive National Medal of Technology and Innovation

ECS member **Adam Heller** (center) received the National Medal of Technology and Innovation in Washington, DC, in September 2008. Joining him at the dinner in honor of the Laureates were (from left to right): *Interface* Editor **Krishnan Rajeshwar**, **Ben Feldman** (see story), Heller, **Tim Goodnow** (Divisional Vice President, Abbott Diabetes Care), and ECS Executive Director **Roque Calvo**.

ECS member **C. Grant Willson** (third from left) received the National Medal of Technology and Innovation in Washington, DC, in September 2008. Joining him at the dinner in honor of the Laureates were (from left to right): *Interface* Editor **Krishnan Rajeshwar**, **Debbie Willson**, Willson, and **Lewis M. Terman** (2008 President of IEEE).

example, the Nobel prizes. In the NMTI case, teams of researchers and companies are also eligible for recognition along with individuals, again unlike other awards and prizes. Out of the "Hall of Fame" of ECS member medalists (see box on page 37), three recent awardees, Adam Heller (2007), C. Grant Willson (2007), and Jerry Woodall (2001), and their contributions are discussed below.

Adam Heller

Adam Heller received his MSc (chemistry and physics, 1957) and PhD (chemistry, 1961) from the Hebrew University, Jerusalem, where he studied under Ernst David Bergmann. Following postdoctoral work at UC Berkeley and at Bell Laboratories, he joined GTE Laboratories becoming Manager of Exploratory Research in 1970. In 1975 he returned to Bell Laboratories, heading from 1977 until 1988 the Electronic Materials Research Department, where he managed research on the materials science underlying high-density, high-frequency chip-interconnections, used in small portable electronic devices. He was appointed to the Ernest Cockrell, Sr. Chair in Engineering at The University of Texas at Austin in 1988 and became one of the university's first research professors in 2002.

Heller built, in 1966, the first inorganic liquid laser. In 1973 he published, with James J. Auborn, the first paper on one of the earliest lithium batteries, the lithium thionyl chloride battery, still manufactured and used worldwide. In 1978 he reported the first 11.5 % efficient photoelectrochemical solar cell, and in 1981 the first photoelectrochemical cell converting sunlight to chemical energy, stored as hydrogen, at 12% efficiency. In 1991 he showed, with the late Heinz Gerischer, that the rate of photocatalytic oxidation of contaminants on small titanium dioxide particles was controlled by the rate of reduction of adsorbed oxygen by trapped electrons. Subsequently, with Michael Pishko and Ephraim Heller, he developed the materials science of binding the photocatalytic particles to surfaces. In 1995-7, with Yaron Paz, he then designed thin, transparent, photo-active films of titanium dioxide nanoparticles on window glass, which made the windows self-cleaning under sunlight, providing a route to the presently manufactured self-cleaning windows.

Heller introduced (1988-1995) the electrical connection ("wiring") of redox centers of enzymes to electrodes through electron-conducting redox hydrogels. The redox hydrogel-wired enzymes effectively catalyze oxidation and reduction reactions of water-soluble biochemicals. Using the wired glucose-oxidation catalyzing enzyme glucose oxidase, he designed subcutaneously implanted miniature glucose sensors, constituting the core of Abbott's FreeStyle Navigator™ continuous glucose monitoring system for diabetes management. The system enables diabetic people to reduce or avoid periods of high glucose, which are the cause of the debilitating complications of diabetes, and blackout-causing periods of low glucose. The high and low periods now exceed 8 hours/day even in those Type 1 diabetic people who most carefully manage their disease, measuring their blood glucose concentrations 9 times/day.

Heller's contributions to science are described in 226 peer reviewed papers, and 17 book chapters and reviews. They were cited more than 13,000 times. This body of research is the basis for five presently manufactured products. His contributions to technology and engineering are described in 102 issued U.S. Patents, 37 of which are in use. Other than the NMTI award, Heller was earlier elected to the U.S. National Academy of Engineering and was made Fellow of the American Association for the Advancement of Science, Fellow of The Electrochemical Society, and Honorary Fellow of the American Institute for Medical and Biological Engineering. He was named Guest Professor of the Collège de France and received honorary doctorates from Uppsala University in Sweden and from Queen's College of the City University of New York.

Other medal recognitions include the Spiers Medal of the Royal Society of Chemistry, UK; the Faraday Medal of the Royal Society of Chemistry, UK; the Medal of the Faculty of Engineering of the University of Tokyo; the Vittorio de Nora Medal of The Electrochemical Society; and the Fresenius Gold Medal and Prize of the Society of German Chemists. His awards include the Grahame Award of The Electrochemical Society; the Battery Research Award of The Electrochemical Society; the Chemistry of Materials Award of the American Chemical Society; the Creative Invention Award of the American Chemical Society; the Reilly Award of the Electroanalytical Society; and the Chemical Engineering Practice Award of the American Institute of Chemical Engineers.

Given below are Dr. Heller's own reflections on the pioneering glucose sensor work. (**Ed. Note:** These are synthesized from two separate interviews he gave to Keren Wulich of *The Globe* and to Krishnan Rajeshwar and Roque Calvo at the National Medal Awards Gala dinner in Washington, DC.)

Diabetes affects 300 million people, which are 5% of the world's population. Its complications are a major cause of blindness, kidney failure, amputation of limbs, nerve degeneration, and vascular disease. Its annual cost to the world economy is more then 100 billion dollars. Diabetes complications can be prevented by tightly controlling the concentration of blood glucose. Tight control, which still leaves the diabetic person above or below the desired glucose concentration range 1/3 of the time (about 8 hours a day), requires frequent (daily ~ 5) blood glucose assays. Six billion glucose assays are performed each year, more than all other analytical assays combined.

My son, Ephraim and I, co-founded TheraSense™ to maintain the health of diabetic people with less pain and better health. Through TheraSense, specifically through FreeStyle™, we succeeded in removing the pain of monitoring by reducing the volume of blood required for the glucose assay and in reducing the complications of diabetes, by developing a continuous glucose monitor, which broadcasts the actual glucose concentration and predicts impending high or low glucose levels. It is a key step in establishing the foundation for an integrated diabetes management system, based on the continuously broadcasting of the glucose concentration from the monitor to an insulin pump.

One of the first people we hired at TheraSense was an electrochemist, Ben Feldman. Next, we added a manufacturing engineer, Phil Plante. Both made key contributions to the success of the company. The initial focus of TheraSense was the enzyme "wiring" based subcutaneously implanted glu-cose sensor for diabetes management. In 1996, Ephraim conceived, and Ben and I designed, a second product, FreeStyle, a microcoulometric blood glucose monitor for diabetes management. It required an order of magnitude less blood than other systems on the market, only 300 nL, a sample so small that it is painlessly obtained. The device takes advantage of the fact that the smaller the blood volume, *i.e.,* the thinner the microcoulometer's liquid layer is, the faster its glucose is electro-oxidized. We designed therefore a thin-layer (50 μm) microcoulometer, in which glucose is selectively electro-oxidized in a few seconds. It is the first mass-produced sub-microliter fluidic device, of which more than a billion units are produced annually. It is also the most accurate blood glucose monitor available to self monitoring diabetic people. It is more accurate than the earlier amperometric blood glucose monitors, because the outcome of coulometry is not affected by temperature, blood viscosity, glucose electro-oxidation catalyzing enzyme activity, or by preferential electro-oxidation of interferants.

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Significant Publications of the Medal Laureates

Listed below are publications that each of the medalists deemed most significant in terms of impact. Annotations are added in some cases.

Adam Heller

1. A. Heller, "High-Gain Room-Tmperature Liquid Laser: Trivalent Neodymium in Selenium Oxychloride," *Appl. Phys. Lett.*, **9**, 106 (1966).
2. J. J. Auborn, K. W. French, S. I. Lieberman, V. K. Shah, and A. Heller, "Lithium Anode Cells Operating at Room Temperature in Inorganic Electrolytic Solutions," *J. Electrochem. Soc.*, **120**, 1613 (1973).
3. A. Heller, B. A. Parkinson, and B. Miller, "A 12% Efficient Semiconductor-Liquid Junction Solar Cell," *Proc. IEEE Photovoltaic Specialists Conference*, **13**, 1253 (1978).
4. A. Heller and R. G. Vadimsky, "Efficient Solar to Chemical Conversion: 12% Efficient Photo-assisted Electrolysis in the [p-type InP(Ru)]/HCl-KCl/Pt(Rh) Cell," *Phys. Rev. Lett.*, **46**, 1153 (1981).
5. H. Gerischer and A. Heller, "The Role of Oxygen in Photo-Oxidation of Organic Molecules on Semiconductor Particles," *J. Phys. Chem.*, **95**, 5261 (1991).
6. A. Heller, "Chemistry and Applications of Photocatalytic Oxidation of Thin Organic Films," *Accounts Chem. Res.*, **28**, 503 (1995).
7. Y. Paz, Z. Luo, L. Rabenberg, and A. Heller, "Photo-oxidative Self-Cleaning Transparent Titanium Dioxide Films on Glass," *J. Mater. Res.*, **10**, 2842 (1995).
8. Y. Paz and A. Heller, "Photo-Oxidatively Self-Cleaning Transparent Titanium Dioxide Films on Soda Lime Glass: The Deleterious Effect of Sodium Contamination and Its Prevention," *J. Mater. Res.*, **12**, 2759 (1997).
9. B. Feldman, G. McGarraugh, A. Heller, N. Bohannon, J. Skyler, E. DeLeeuw, and D. Clarke, "FreeStyle: A Small-Volume Electrochemical Glucose Sensor for Home Blood Glucose Testing," *Diabetes Technology & Therapeutics*, **2**, 221 (2000).
10. A. Gregg and A. Heller, "Cross-Linked Redox Gels Containing Glucose Oxidase for Amperometric Biosensor Applications," *Anal. Chem.*, **62**, 258 (1990).

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Significant Publications...

(*Adam Heller, cont'd.*)

11. A. Heller, "Electrical Connection of Enzyme Redox Centers to Electrodes," *J. Phys. Chem.*, **96**, 3579 (1992).

12. E. Csoeregi, D. W. Schmidtke, and A. Heller, "Design and Optimization of a Selective Subcutaneously Implantable Glucose Electrode Based on 'Wired' Glucose Oxidase," *Anal. Chem.*, **67**, 1240 (1995).

13. J. G. Wagner, D. W. Schmidtke, C. P. Quinn, T. F. Fleming, B. Bernacky, and A. Heller, "Continuous Amperometric Monitoring of Glucose in a Brittle Diabetic Chimpanzee with a Miniature Subcutaneous Electrode," *Proc. Nat. Acad. Sci.*, **95**, 6379 (1998).

14. A. Heller and B. Feldman, "Electrochemical Glucose Sensors and Their Applications in Diabetes Management," *Chem. Rev.*, **108**, 2482 (2008).

C. Grant Willson

1. W. Heath, F. Palmieri, J. Adams, B. Long, J. Chute, T. Holcombe, S. Zieren, M. Truitt, J. White, and C. G. Willson, "Degradable Cross-Linkers and Strippable Imaging Materials for S-FIL," *Macromolecules*, **41**, 719 (2008).

2. K. Wu, X. Wang, E. K. Kim, C. G. Willson, and J. G. Ekerdt, "Experimental and Theoretical Investigation on Surfactant Segregation in Imprint Lithography," *Langmuir*, **23**, 1166 (2007).

3. F. Palmieri, J. Adams, B. Long, W. Heath, P. Tsiartas, and C. G. Willson, "Design of Reversible Cross-Linkers for Step and Flash Imprint Lithography Imprint Resists," *ACS Nano*, **1**, 307 (2007).

4. B. K. Long, B. Keitz, B. Keith, and C. G. Willson, "Materials for Step and Flash Imprint Lithography (S-FIL)," *J. Mater. Chem.*, **17**, 3575 (2007).

5. W. L. Jen, F. Palmieri, B. Chao, M. Lin, J. Hao, J. Owens, K. Sotoodeh, R. Cheung, and C. G. Willson, "Multilevel Step and Flash Imprint Lithography for Direct Patterning of Dielectrics," *Proc. SPIE*, **19**, 6517 (2007).

6. R. Pawloski, A. Acheta, H. J. Levinson, T. B. Michaelson, A. Jamieson, Y. Nishimura, and C. G. Willson, "Line Edge Roughness and Intrinsic Bias for Two Methacrylate Polymer Resist Systems," *J. Microlith., Microfab., Microsyst.*, **5**, 023001 (2006).

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In 1996 the company developed, tested and manufactured on a pilot scale (> 10^4 units per day) the painless home blood glucose monitor. In 1996 the company was financed by venture capital and at the end of 1996, Mark Lortz, formerly the VP of Operations of J&J Lifescan, was hired as the new CEO of the company. The U.S. FDA approved the painless, 300 nL blood sample-analyzing, glucose monitor of TheraSense for use by diabetic people in 2000. This monitor, marketed under the name FreeStyle assayed the glucose concentration in 300 nanoliters of blood. This blood volume, about 1/8th of a typical mosquito blood meal, is small enough to be painlessly obtained. With more than a billion units produced annually, FreeStyle is arguably the highest impact nanotechnological or microfluidic device to-date.

Using the wired glucose-oxidation catalyzing enzyme glucose oxidase, we have designed subcutaneously implanted miniature glucose sensors. These are the core of the Abbott's FreeStyle Navigator continuous glucose monitoring system for diabetes management. The system enables diabetic people to reduce or avoid periods during which their glucose levels are high, increasing the prevalence of complications of diabetes, or low, increasing the risk of blackouts.

C. Grant Willson

C. Grant Willson joined the faculties of the Departments of Chemical Engineering and Chemistry at the University of Texas at Austin in 1993. He received his BS and PhD in organic chemistry from the University of California at Berkeley and an MS degree in organic chemistry from San Diego State University. He came to the University of Texas from his position as an IBM Fellow and Manager of the Polymer Science and Technology area at the IBM Almaden Research Center in San Jose, California. He joined IBM after serving on the faculties of California State University, Long Beach and the University of California, San Diego.

Dr. Willson's research can be characterized as the design and synthesis of functional organic materials with an emphasis on materials for microelectronics. These include monomeric and polymeric liquid crystalline materials, polymeric non-linear optical materials, novel photoresist materials, etc. He is co-inventor of the chemically amplified photoresists used to manufacture all of today's advanced semiconductor devices, and is co-founder of Molecular Imprints, Inc.

Dr. Wilson will receive the 2009 ECS Gordon E. Moore Medal for Outstanding Achievement in Solid-State Science and Technology at the upcoming ECS meeting in San Francisco. He is a member of the ACS, APS, SPIE, SPE, AAAS, ASEE, and Sigma Xi; a Fellow of PMSE and SPIE; and a member of the National Academy of Engineering. He is an associate editor of one ACS journal and serves on the editorial boards of several others. He is the co-author of more than 400 journal publications and the editor and author of several books, and co-inventor on more than 50 issued patents.

Dr. Willson's work has been honored by the Arthur Doolittle Award, the Chemistry of Materials Award, the Carothers Award from the American Chemical Society, the Alexander von Humboldt Senior Scientist Award from the Federal Republic of Germany, the ACS Award for Cooperative Research in Polymer Science and Engineering, the SRC Technical Excellence Award, the SRC Aristotle Award, and the Malcolm E. Pruitt Award from the CRC. He is the recipient of the 1999 National Academy of Sciences Award for Chemistry in Service to Society. He was appointed Fellow of the PMSE Division of ACS in 2001 and received the Applied Polymer Science Award from the ACS in that year. In 2003 he received the Photopolymer Science and Technology Award in Japan and in 2005 he received the Dehon Little Award from the AIChE, the Zernike Award from the SPIE, and the Heroes in Chemistry Award from the ACS. In 2007 he was elected a Fellow of SPIE and was the recipient of the SEMI North America Award and the Presidential Medal for Technology and Innovation.

The attribution for the Medal was "For creation of novel lithographic imaging materials and techniques that have enabled the manufacturing of smaller, faster and more efficient microelectronic components that better the quality of the lives of people worldwide and improve the competitiveness of the U.S. microelectronics."

Jerry M. Woodall

Woodall began his research career at IBM in 1962, becoming a Fellow of the renowned Thomas J. Watson Research Center in 1985. He completed a BS in metallurgy from MIT and a PhD in electrical engineering from Cornell University. He held the Charles William Harrison Distinguished Professorship of Microelectronics at Purdue University from 1993 through 1999. After stints as the C. Baldwin Sawyer Professor of Electrical Engineering at Yale University and the Chief Science

Officer of LightSpin Technologies, Inc, Woodall currently holds the Barry M. and Patricia L. Epstein Distinguished Professor of Electrical and Computer Engineering at Purdue University.

In a career spanning more than four decades, Jerry M. Woodall has conducted pioneering research in compound semiconductor materials and devices, touching off an explosion of research and commercial development in related fields. The cellular phone, the TV remote control, the CD player, local-area networks (LANs) used in computing, the solar cells on the Mars Pathfinder Space Probe—all these devices, and others, stem from Woodall's work.

Woodall's most significant accomplishments are his co-invention and development of the liquid-phase epitaxial growth of gallium aluminum arsenide (GaAlAs), and the co-invention of the gallium aluminum arsenide-gallium arsenide (GaAlAs/GaAs) heterojunction. GaAlAs epitaxial layers form the bases of many important commercial high-speed electronic and photonic devices, including super-bright red LEDs, solid-state lasers, and ultra-fast transistors. The GaAlAs/GaAs interface currently comprises the most important compound semiconductor heterojunction. It is commercially important for electronic and photonic devices, and it has led to such new areas of solid-state physics as superlattice, low-dimension, mesoscopic, and resonant tunneling physics.

In addition, Woodall pioneered the horizontal Bridgman growth of both high-purity GaAs crystals, used for the first definitive measurement of the carrier velocity-electric field relationships for GaAs, and highly perfect GaAs crystals used to fabricate early injection lasers. He then pioneered and patented the development of the liquid-phase epitaxy of silicon-doped GaAs high-efficiency light-emitting diodes (LEDs), devices found in the now ubiquitous TV remote control and in infrared LANs. He followed this work with the invention of GaAlAs and GaAlAs/GaAs heterojunctions used in super-bright-red LEDs and lasers used, for example, in CD players and short-link optical fiber communications. Further breakthroughs include the patenting of a bipolar transistor used in cellular phones (and other applications) and the development of the pseudomorphic high-electron-mobility transistor (HEMT), a state-of-the-art high-speed device widely used in commercial devices and circuits and employed in the creation of "self-organized" quantum dots, a topic of intense interest in physics. Woodall's current work involves the epitaxial growth of III-V materials and devices with special emphasis on metal contacts and doping studies. More than half the estimated $5 billion world market for GaAs-based electronic and photoelectronic devices involves GaAlAs/GaAs heterojunction devices of the kind that have grown out of his efforts.

Woodall's efforts are recorded in more than 275 publications in the open literature, 67 issued U.S. patents, and 1 patent pending. He has received five major IBM Research Division Awards, 30 IBM Invention Achievement Awards, and an IBM Corporate Award in 1992 for the invention of the GaAlAs/GaAs heterojunction. Other recognition includes 9 NASA certificates of recognition; a 1975 IR-100 Award; the 1980 Electronics and Photonics Division Award of The Electrochemical Society (ECS); the 1985 ECS Solid State Science and Technology Award; the 1990 American Vacuum Society's (AVS) Medard Welch Award, its highest honor; the 1998 American Society for Engineering Education's General Electric Senior Research Award; and the 1998 Edward Goodrich Acheson Award from ECS, one of its highest honors.

Woodall was elected to the National Academy of Engineering in 1989 and is a Fellow of ECS, the American Physical Society, IEEE, and AVS. He has served as President of ECS and AVS and is a member of the American Institute of Physics Board of Directors and Executive Committee. In 1997-98 Eta Kappa Nu recognized him with its Vladimir Karapetoff Eminent Member's Award for "the invention of the GaAlAs/GaAs heterojunction, and for the invention, development, and realization of devices that use this materials system. These include light-emitting diodes, lasers, heterojunction transistors, and solar cells." (This award recognizes only those inventions that have had a significant impact on society.) Woodall also received IEEE's Jack A. Morton Award in 1984 for "pioneering work in GaAlAs heterojunctions and high-efficiency light-emitting diodes and injection lasers prepared by liquid-phase epitaxy;" and the Gallium Arsenide Symposium Award and Heinrich Welker Gold Medal in 1988 for his "pioneering work introducing the III-V alloy GaAlAs and his further fundamental contributions to III-V compound semiconductor physics." The NMTI award citation reads, "For the invention and development of technologically and commercially important compound semiconductor heterojunction materials, processes, and related devices, such as light-emitting diodes, lasers, heterojunction transistors, and solar cells."

Reproduced are Woodall's remarks at the Department of Commerce award ceremony, upon receiving the NMTI Medal.

> I want to express my appreciation and gratitude to all those at the Department of Commerce associated

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Significant Publications...

(*C. Grant Willson, cont'd.*)

7. C. Taylor, R. J. LeSuer, C. R. Chambers, F-R. F. Fan, A. J. Bard, W. E. Conley, and C. G. Willson, "Experimental Techniques for Detection of Components Extracted from Model 193 nm Immersion Lithography Photoresists," *Chem. Mater.*, **17**, 4194 (2005).

8. E. K. Kim, M. D. Stewart, K. Wu, F. L. Palmieri, M. D. Dickey, J. G. Ekerdt, and C. G. Willson, "Vinyl Ether Formulations for Step and Flash Imprint Lithography," *J. Vac. Sci. Technol. B*, **23**, 2967 (2005).

9. D. Gates, Q. Xu, M. Stewart, R. Deschner, C. G. Willson, and G. Whitesides, "New Approaches to Nanofabrication: Molding, Printing, and Other Techniques," *Chem. Rev.*, **105**, 1171 (2005).

10. G. M. Schmid, M. D. Stewart, S. D. Burns, and C. G. Willson, "Mesoscale Monte Carlo Simulation of Photoresist Processing," *J. Electrochemical Soc.*, **151**, G155 (2004).

11. M. Colburn, B. J. Choi, S. V. Sreenivasan, R. T. Bonnecaze, and C. G. Willson, "Ramifications of Lubrication Theory on Imprint Lithography," *Microelec. Eng.*, **75**, 321 (2004).

12. M. D. Stewart, H. V. Tran, G. M. Schmid, T. B. Stachowiak, D. J. Becker, and C. G. Willson, "Acid Catalyst Mobility in Resist Resins," *J. Vac. Sci. & Tech. B*, **20**, 2946 (2002).

13. S. Johnson, D. J. Resnick, D. Mancini, K. Nordquist, W. J. Dauksher, K. Gehoski, J. H. Baker, L. Baker, A. Dues, A. Hooper, T. C. Bailey, S. V. Sreenivasan, J. G. Ekerdt, and C. G. Willson, "Fabrication of Multi-Tiered Structures on Step and Flash Imprint Lithography Templates," *Microelec. Eng.*, **67-68**, 221 (2003).

14. G. Willson, B. C. Trinque, B. P. Osborn, C. R. Chambers, Y. T. Hsieh, T. Chiba, P. Zimmerman, D. Miller, and W. Conley, "The Design of Resist Materials for 157 nm Lithography," *J. Photopolymer Sci. & Tech.*, **15**, 583 (2002).

15. M. Colburn, S. Johnson, S. Damle, T. Bailey, B. Choi, M. Wedlake, T. Michaelson, S. V. Sreenivasan, J. Ekerdt, and C. G. Willson, "Step and Flash Imprint Lithography: A New Approach to High-Resolution Patterning," *Proc. SPIE*, **3676**, 379 (1999).

16. P. C. Tsiartas, L. W. Flanagin, C. L. Henderson, W. D. Hinsberg, I. C. Sanchez, R. T. Bonnecaze, and C. G. Willson, "The Mechanism of Phenolic Polymer Dissolution: A New Perspective," *Macromolecules*, **30**, 4656 (1997).

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Significant Publications…

(*C. Grant Willson, cont'd.*)

17. S. A. MacDonald, W. D. Hinsberg, H. R. Wendt, N. J. Clecak, C. G. Willson, and C. D. Snyder, "Airborne Contamination of a Chemically Amplified Resist. 1. Identification of Problem," *Chem. Mater.*, **5**, 348 (1993).

18. J. G. Maltabes, S. J. Holmes, J. R. Morrow, R. L. Barr, M. Hakey, G. Reynolds, W. R. Brunsvold, C. G. Willson, N. Clecak, S. MacDonald, and H. Ito, "1X Deep UV Lithography with Chemical Amplification for 1-Micron DRAM Production," Advances in Resist Technology and Processing VII, *Proc. SPIE*, **1262**, 2 (1990).

19. C. G. Willson, H. Ito, J. M. J. Frechet, and F. Houlihan, "Chemical Amplification in the Design of Polymers for Resist Applications," *IUPAC*, **28**, 448 (1982).

20. C. G. Willson, H. Ito, and J. M. J. Frechet, "L'Amplification Chimique Appliquée au Dévelopement de Polymères Utilisables Comme Résines de Lithographie," *Colloque Inter. sur la Microlithographie: Microcircuit Engineering*, **82**, 261 (1982).

Jerry Woodall

1. H. Rupprecht, J. M. Woodall, K. Konnerth, and D. G. Pettit, "Efficient Electro-luminescence from GaAs Diodes at 300K," *App. Phys. Lett.*, **9**, 221 (1966). This was the first report of a high-efficiency LED, the first fabrication of an LED by the liquid-phase epitaxy (LPE) method, and the first use of Si as both an n-type and p-type dopant. To date, this LED remains the LED of choice for IR signal, control, and IR LAN. It is covered by a U.S. patent.

2. H. Rupprecht, J. M. Woodall, and G. D. Pettit, "Efficient Visible Electroluminescence at 300K from GaAlAs p-n Junctions Grown by Liquid Phase Epitaxy," *Appl. Phys. Lett.*, **11**, 81 (1967). The first useful demonstration of the lattice-matched heterojunction, this publication opened the field of heterojunction research in general.

3. J. M. Woodall and H. J. Hovel, "High Efficiency $Ga_{1-x}Al_xAs$ - GaAs Solar Cells," *Appl. Phys. Lett.*, **21**, 379 (1972). This seminal publication demonstrated the use of GaAlAs/GaAs for high-efficiency solar cells and showed that this heterojunction greatly reduced surface recombination in GaAs.

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with the award of the National Medal of Technology, and particularly to Secretary Evans, Deputy Secretary Bodman, and Under Secretary Bond. I also want to thank my colleagues, especially Hans Rupprecht and Seymour Keller, who, over the years have contributed so much to my personal success in the laboratory, and to my friends and relatives for their enthusiasm and support of my career. In this regard, I want to acknowledge my cousin, David Brownwood, who is here today, who grew up with me, and, being several years older than I, would come home from school and teach me everything he had learned that day!

Finally, I want to give special thanks to Mildred Porter for her tireless and patient effort to pull this thing off, and, who showed me that planning for events at the White House is best expressed by the word "fickle." Seriously though, I am truly overwhelmed by this honor. For in my youth and college days I was on no one's list as a person most likely to succeed. I was a poor or at least no better than an average undergraduate student during my time at MIT, graduating with a C average and flunking my E&M course along the way! However, thanks to Prof. Morris Cohen, who took me on as my undergraduate thesis advisor, I discovered that I was good in the laboratory. And the rest, as they say, is history. And now my life's work on compound semiconductor heterojunctions and heterojunction-based materials and devices is being honored and at the very highest level. So, I am now a happy camper invigorated to return to the laboratory and classroom to mentor students to follow in my footsteps.

Since the NMTI award in 2001, we are happy to report that Jerry Woodall has not been resting on his laurels at all. His latest passion is the problem of hydrogen generation and storage. In his view, elemental aluminum (Al) has the potential to be a commercially viable means of reaching such a goal. While it is well documented that it is thermodynamically possible to react Al with water to produce hydrogen gas, aluminum oxide (alumina), and heat, the self-passivating nature of pure Al into alumina in air or water has prevented this from being exploited on a large scale. However, in the late 1960s, while at IBM Research, Woodall discovered that liquid alloys of gallium (Ga) and Al are capable of disrupting the passivating alumina layer thus enabling the Al to produce hydrogen from water. Much more recently, researchers at Purdue University, under Prof. Woodall's supervision, have shown that bulk solid alloys comprised of 95% Al and a 5% mixture of Ga, indium (In), and tin (Sn) were capable of this same reaction at room temperature. This reaction has a total theoretical energy density of 8.6 kWh/kg of Al, 4.4 kWh of which is the heat of combustion of hydrogen, and 4.2 kWh of which is heat. This reaction would provide a significantly higher energy density than both traditional and modern chemical batteries.

The Al-(Ga,In,Sn) alloy system can be used to produce on-demand hydrogen gas from water for portable power applications and potable water generation. Three relevant issues contribute to the life-cycle inventory of this system. First, large-scale manufacturing of the alloy will be possible using either current inventories of scrap Al (400 billion kg) or available reserves of bauxite (10 trillion kg) and Ga produced as a byproduct of Al manufacturing. Second, the Ga, In, and Sn in the alloy are inert and can therefore be completely recovered for reuse in future alloy products to reduce costs. Third, the alumina product of the reaction can be electrolyzed back to Al at a current efficiency of 12.9 kWh/Kg of Al, which allows this method of energy storage and transport to be sustainable indefinitely. Therefore, an economically viable life cycle inventory for large-scale hydrogen generation could be accomplished by expanding current production capacity. Woodall reckons that lifecycle impact assessment of this production expansion would require local carbon sequestration at the smelter or employing carbon neutral electrodes for the electrolysis.

Concluding Remarks

It is abundantly clear from the preceding paragraphs (and from the contents of this celebratory special issue of the magazine in general) that ECS members have carved an impressive niche in the annals of scientific achievements. While as illustrated above, Adam Heller, Grant Willson, and Jerry Woodall are three shining examples of such individuals whose contributions have been recognized by organizations outside of the Society, others (*e.g.*, Rudy Marcus and Gordon Moore) were featured in these magazine pages in previous issues. ECS is proud to claim all these "Hall of Famers" as members of its family. The pronoun "great" is often used lightly but it certainly applies to describe these scientists.

Significant Publications...

(*Jerry Woodall, cont'd.*)

4. W. P. Dumke, J. M. Woodall, and V. L. Rideout, "GaAs-GaAlAs Heterojunction Transistor for High Frequency Operation," *Solid State Electronics*, **15**, 1339 (1972). This research marked the first realization of HBTs and forms the basis of the power amplifier stage of current cellular phones.

5. J. Rosenberg, M. Benlarmi, P. D. Kirchner, J. M. Woodall, and G. D. Pettit, "An InGaAs/GaAs Pseudomorphic Single Quantum Well HEMT," *IEEE Electron Device Lett.*, **6**, 491 (1985). This paper describes what continues to be the device of choice for low-noise small-signal amplification in many applications, including cellular phones.

6. D. L. Rogers, J. M. Woodall, G. D. Pettit, and D. McInturff, "High Performance, 1.3 Micron, GaInAs Detectors Fabricated on GaAs Substrates," *IEEE Electron Device Lett.*, **9**, 515 (1988). This is the first demonstration of an enabler to allow the integration of InGaAs 1.3-1.5 photonic devices with GaAs high-speed electronic circuits.

7. J. M. Woodall, J. Freeouf, G. D. Pettit, T. N. Jackson, and P. D. Kirchner, "Ohmic Contacts to n-GaAs Using Graded Band Gap Layers of GaInAs Grown by MBE," *J. Vac. Sci. & Tech.*, **19**, 626 (1981). This is a state-of-the-art ohmic contact widely used by companies that fabricate HBTs for applications that include cellular phones.

8. P. E. Dodd, M. L. Lovejoy, M. S. Lundstrom, M. R. Melloch, J. M. Woodall, and J. D. Pettit, "Demonstration of npn InAs Bipolar Transistors with Inverted Base Doping," *IEEE Electron Device Lett.*, **17**, 166 (1996). This is the first reported demonstration of an InAs-based bipolar transistor. It is important because it offers the possibility of terahertz frequency performance.

9. S. Tiwari, G. D. Pettit, R. J. Davis, and J. M. Woodall, "High Efficiency and Low Threshold Current Strained V-Groove Quantum-Wire Lasers," *Appl. Phys. Lett.*, **64**, 3536 (1994). This was the first demonstration of an injection laser with threshold currents well below 1 mA, opening the possibility for realistic optical interconnects for high-density integrated electronic circuits.

10. R. C. Gee, T. P. Chin, C. W. Tu, P. M. Asbeck, C. L. Lin, P. D. Kirchner, and J. M. Woodall, "InP/InGaAs HBTs Grown by GSMBE with Carbon Doped Base," *IEEE Electron Device Lett.*, **13**, 247 (1992). This HBT device is thought to be a strong candidate for the next-generation technology for cellular phones. It was demonstrated through a manufacturing technology of choice.

11. J. J. Cuomo, J. F. Ziegler, and J. M. Woodall, "A New Concept for Solar Energy Thermal Conversion," *Appl. Phys. Lett.*, **26**, 557 (1975). This was a revolutionary way to efficiently convert solar energy into heat.

12. S. D. Offsey, J. M. Woodall, A. C. Warren, P. D. Kirchner, T. C. Chappell, and G. D. Pettit, "Unpinned (100) GaAs Surfaces in Air Using Photochemistry," *Appl. Phys. Lett.*, **48**, 475 (1986). This was a seminal demonstration that the problem of Fermi-level pinning at GaAs surfaces could be eliminated and, hence, was not due to a fundamental physical limitation. This opened the way to the subsequent demonstration of a GaAs MOS technology and new surface passivation techniques.

13. J. Freeouf and J. M. Woodall, "Schottky Barriers: An Effective Workfunction Model," *Appl. Phys. Lett.*, **39**, 727 (1981). This paper provided a new way of understanding Fermi-level pinning at compound semiconductor surfaces. Its technological implications led to, e.g., the results of paper 12 above.

14. J. M. Woodall, G. D. Pettit, T. N. Jackson, C. Lanza, K. Kavanaugh, and J. Meyer, "Fermi-Level Pinning by Misfit Dislocations at GaAs Interfaces," *Phys. Rev. Lett.*, **51**, 1783 (1983). This is a fundamental inter-face physics study demonstrating a new mechanism for Fermi-level pinning at lattice mismatched interfaces.

15. J. C. P. Chang, T. P. Chin, and J. M. Woodall, "Incoherent Interface of InAs Grown Directly on GaP(100)," *Appl. Phys. Lett.*, **69**, 981 (1996). This is a seminal paper showing that good-quality epilayers of InAs can be grown on GaP substrates. This is a revolutionary result, as it was widely believed that high-quality epilayers of materials with a large lattice constant mismatch relative to the substrate could not be successfully grown. (InAs/GaP has an 11% lattice mismatch.)

16. M. D. Pashley, K. W. Haberern, W. Friday, J. M. Woodall, and P. D. Kirchner, "The Structure of GaAs (001) (2x4)-c(2x8) Determined by Scanning Tunneling Microscopy," *Phys. Rev. Lett.*, **60**, 2176 (1988). The very first report of scanning tunneling microscopy of MBE-grown GaAs surfaces, this paper was cited at the plenary session of the International Conference of the Physics of Semiconductors, 1988, Warsaw, Poland. It was the first experimental proof of current theories for the atomic structure of GaAs surfaces.

17. L. J. Brillson, M. L. Slade, R. E. Viturro, M. K. Kelly, N. Tache, G. Margaritondo, J. M. Woodall, P. D. Kirchner, G. D. Pettit, and S. L. Wright, "Absence of Fermi-Level Pinning at Metal-InGaAs(100) Interfaces," *Appl. Phys. Lett.*, **48**, 1458 (1986). A seminal paper that demonstrates Schottky limit behavior (no Fermi-level pinning) for MBE-grown GaInAs and low-temperature deposition of metals. It also demonstrates the validity of paper 13 above.

18. J. M. Woodall, "Solution Grown $Ga_{1-x}Al_xAs$ Superlattice Structures," *J. Crystal Growth*, **12**, 32 (1972). The first report of fabricating superlattice structures using GaAlAs/GaAs materials. The invention of the semiconductor superlattice and its physics on GaAlAs/GaAs has led to many prizes and awards.

19. R. M. Feenstra, J. M. Woodall, and G. D. Pettit, "Observation of Bulk Defects by Scanning Tunneling Microscopy and Spectroscopy: Arsenic Antisite Defects in GaAs," *Phys. Rev. Lett.*, **71**, 1176 (1993). This paper is the seminal work on the electronic properties of As-related defects described in paper #20 below.

20. C. Warren, J. M. Woodall, J. L. Freeouf, D. Grischkowsky, D. T. McInturff, M. R. Melloch, and N. Otsuka, "Arsenic Precipitates and the Semi-Insulating Properties of GaAs Buffer Layers Grown by Low Temperature Molecular Beam Epitaxy," *Appl. Phys. Lett.*, **57**, 1331 (1990). This is the first report of the properties of As precipitates in GaAs grown by MBE at low substrate temperatures. Since this publication, the authors have demonstrated many important applications including launching a company that has commercialized a state-of-the-art high-speed photodetector.