TECHNOLOGY

by Cindy Bruckner-Lea, George K. Celler, Robert G. Kelly, Jean Lessard
Robert D. McConnell, Katsumi Niki, and Krishnan Rajeshwar

"Prediction is very hard, especially when it's about the future" — Yogi Berra

Prediction is hard, and in the technology world, it can even be a foolhardy exercise. Yet, as we come to the end of the 20th century—a century that saw us reach the moon, split the atom, and crack the genetic code—it is only natural to ask what the 2lst century will hold for us. In doing so, it is also instructive to pause and glance back at what has been accomplished in the last century, perhaps also with a view to learn from the missed opportunities of the past.

We chose a crystal ball for our theme because it carries several levels of meaning—the connotation of gazing into the future (and the past) as well as a tongue-in-cheek reference to the material (as in crystal growth) prevalent in so much of our research. A ball is also representative of the global outlook we all must now incorporate into our working lives.

When we set our crystal ball on the new century, we see a future increasingly shaped by technology. Our lives will change more swiftly than ever. Indeed, looking 100 years ahead can seem surreal when it is difficult to see 100 days ahead. Yet one enduring trait of the human species has been its undying optimism. Despite wars, natural epidemics, and disasters, most would agree that the quality of life today is better than it ever was.

We undertake this journey into the future (with an eye on the past) in three areas that encompass electrochemistry and solid-state science and technology—namely, energy sources, materials, and manufacturing processes. Why these three categories among a choice of any number of other discussion topics? Arguably the most spectacular gains from technological innovations have occurred in the broad realm of materials and industrial processes. These gains have featured order-of-magnitude changes in two aspects, namely, scale and speed. On the other hand, the pollution spewing from tailpipes and chimneys is a constant reminder to us that the energy needed for tomorrow's technologies must come from sources cleaner than fossil fuels. Let us examine first what's in store for us in clean energy sources.

Energy Sources

Although the earth's supply of carbon-based fuels will sustain the energy needs of humanity for many decades to come, there is little doubt that we cannot continue to burn them at the present rate. The already tangible effects of over-reliance on a fossil-based energy economy (*e.g.*, smog, breathing disorders, global warming) increasingly remind us of the need to turn to cleaner forms of energy.

Renewable Energy Sources

In 1997, about 52% of U.S. power came from coal-fired plants, according to figures from the U.S. Department of Energy. Another 18% came from nuclear plants, 14% from gas-fired plants, and 10% from hydroelectric power sources. Interestingly, power from renewable geothermal, wind, and solar energy sources combined accounted for less than 1%. Proponents of renewable energy, however, are convinced that the next century will belong to them, especially as regulators continue to crack down on pollution, and technology advances raise the generating capacity of alternative energy sources. Of these, wind power, biomass, and solar energy appear to hold the most promise. We focus here on the last source, especially the photovoltaic solar energy conversion approach.

Solar photovoltaic energy conversion saw two major discoveries—crystalline silicon (1954) and amorphous silicon

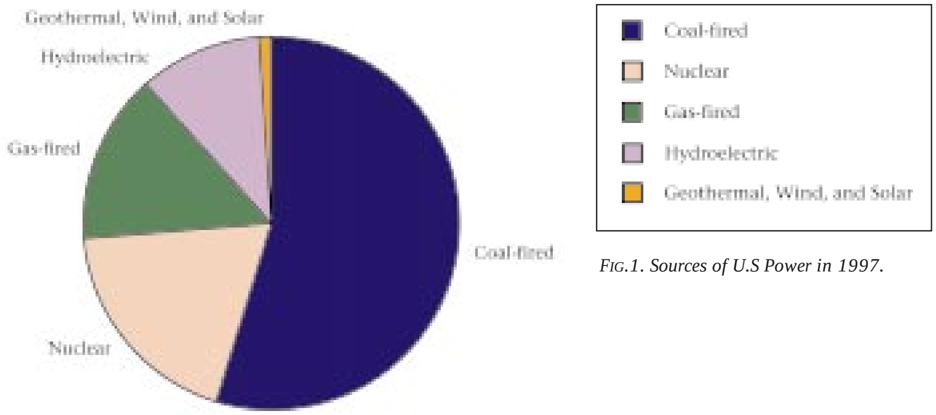


FIG. 1. Sources of U.S Power in 1997.

solar cells (1974). The significance of the first discovery was a dramatic, approximately ten-fold increase in the solar conversion efficiency from those of the older solar electric technology. In the previous century, the photovoltaic effect was merely a laboratory curiosity. The later discovery of the amorphous silicon solar cell was important because it represented a new generation of thin-film devices using a hundred times less semiconductor material. Not only were these devices economically viable as a result but they could also be readily mass-produced. Millions of amorphous silicon-based devices soon appeared in the form of solar-powered watches and calculators.

Notwithstanding these advances, it is pertinent to note that the sunlight-to-electricity conversion efficiencies of these devices to date are far below theoretical limits. For example, the projected limit of around 60% is almost twice that realized experimentally thus far, around 32%. Commercial solar cells operate typically at ~15% efficiency. The limiting costs of these cells have to do with the encapsulant needed for environmental protection, the electrical contacts, and the "active" semiconductor material itself needed for the energy conversion process. Thin film-based devices appear to hold the edge relative to their single crystal counterparts in terms of achieving the needed cost threshold to penetrate the U.S. marketplace (a few cents per kW-h).

The economic issues are complicated because the electricity costs vary widely geographically. Many governments (*e.g.*, Germany and Japan) are subsidizing the installation of solar-powered systems.

The cost challenges in the future, however, will be met through a variety of approaches including:

- the development of silicon solar cells using less costly and lower purity silicon;
- thin-film devices; and
- manufacturing processes requiring significantly lower capital investment (*i.e.*, equipment costs).

The challenges of improving the solar conversion efficiency will be met by the continued development of:

- multijunction devices tuned to two or more colors in the solar spectrum;
- alternative photovoltaic concepts involving new-generation active materials and junctions; and
- sunlight concentrator technology and associated optics.

If anybody doubts the future of renewable energy sources, the fact that established energy producers are bidding to become major suppliers of these new sources ought to be ample testimony to the notion that renewable energy sources will become a technological reality in the next century.

Transportation and Fuel Cells

Transportation needs of the future will be increasingly met by zero and ultra-low emission vehicles. As already featured in these magazine pages (see sidebar below), several manufacturers have already come out with hybrid electric cars. These cars are equipped with both the traditional internal-combustion engine and a battery-driven electric motor. Under normal driving conditions, the car uses battery power to assist the combustion engine. As the car slows down, the electric motor turns into a generator to recharge the batteries. The cars need not be plugged in overnight as do their all-electric counterparts.

"Much R&D in the fuel cell area will continue to focus on the development of onboard fuel processors or 'reformers' to obtain hydrogen from liquid fuel precursors."

There are intense R&D efforts underway to develop fuel cell-powered electric vehicles. At least six different types of fuel cells have been demonstrated for electric power generation, but not all of them are suited to transportation needs. For automotive applications, the commercially available fuels are conventional gasoline and diesel, with limited availability of alternative fuels such as methanol, ethanol, natural gas, and various other fuel blends. Hydrogen would be the optimum fuel for vehicular fuel cell applications because of its energy density. However, a refueling infrastructure (*i.e.*, distribution, storage, and marketing)

Hybrid Cars

The knock on electric cars — apart from the cost — is their limited range. Few buyers are willing to take frequent pitstops for recharging the batteries. On the other hand, the Prius (manufactured by Toyota Motor Co.) has no plug-in provision. It is a parallel hybrid that has two separate drivetrains, one traditional, and the other electric run by NiMH batteries. All electric charging is done by the gasoline-owered engine. The advantage of the hybrid approach is that when a gasoline engine is particularly inefficient — idling in traffic, for example — the car operates on the battery and the engine is shut off. The battery power supplements the small gasoline engine when major acceleration is needed.

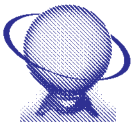
—Excerpted from Interface, *Summer 1999, page 13*

for hydrogen fuel is completely lacking at present. Much R&D in the fuel cell area will continue to focus on the development of onboard fuel processors or "reformers" to obtain hydrogen from liquid fuel precursors.

Stationary power systems with 200 kW-2 MW capacity have already been demonstrated for at least three different fuel cell types—phosphoric acid, molten carbonate, and solid oxide. For these applications, natural gas is an attractive fuel because of its ready availability in most urban areas. On the other hand, it is not a strong fuel contender for transportation applications because of its relatively low energy density. In almost all of these stationary fuel cell applications, the natural gas fuel is converted to hydrogen by catalytic steam reforming, often within the fuel cell stack or bundle itself.

Energy Sources of the Future

Our crystal ball into the future sees an energy economy largely based on non-fossil fuel derived (clean) sources of power. In the interim, drastic reduction in the direct combustion of fossil fuels and their alternative utilization (*e.g.*, as hydrogen precursors) will ensue. Indeed the trend will be toward a distributed energy utilization system (*i.e.*, putting generation close to consumption) rather than the present centralized approach. Some energy will also be produced using modern windmill designs. Much of the energy needed will be generated on site, either in homes or businesses, using a combination of rooftop solar panels, photovoltaic converters, and stationary fuel cell systems. Hydrogen will be produced when the sun is not shining via water electrolysis. This hydrogen in turn will be utilized to power the fuel cell unit.



"...the trend will be toward a distributed energy utilization system, that is, putting generation close to consumption..."

Personal power plants will evolve a long way from their current status in the 20th century, when they were mostly recreational camping curiosities. In the future, will the excess electricity generated at homes and businesses then be sold by the consumer back to the grid? Will we see the development of "micropower" sources for bio-applications such as tiny, implantable batteries that will utilize the body fluids for their operation? Will electrical energy sources play a role in therapy (*e.g.*, cancer treatment)? Even more drastically different transportation concepts can be envisioned based on magnetic or air levitation, especially if developments in superconductors undergo a quantum leap.

Materials

Plastics and semiconductors (especially silicon) comprise two of the more spectacular success stories of the past century. Interestingly enough, the search for a substitute for ivory for making billiard balls was perhaps the driver for the discovery of plastics! Celluloid, the first plastic, was a poor substitute for ivory—the balls often exploded on impact. No good alternative was found until 1907 when Bakelite (see page 29) was invented.

Wartime needs underpinned the development of nylon and synthetic rubber. Small-scale production of synthetic rubber began in Germany in 1910, but economic reasons precluded this material from being little more than a novelty until the outbreak of World War II. U.S. sources of natural rubber in East Asia (available at prices as low as 5¢ a pound) were curtailed by Japanese troops. This in turn led to the intense R&D on styrene-butadiene rubbers in the U.S. DuPont's development of nylon in the 1930s, largely for women's hosiery, turned into a blockbuster when the war co-opted its use as a parachute fabric. Since then, the use of nylon (and other polymers) in consumer applications has seen a quantum leap, and the annual production of these materials in the U.S. alone is in the billions of pounds.

Vacuum tubes were the critical transmission and amplification technology of the first half of the 20th century. They even found application in the earliest computers. But the advent of silicon and the first transistor in June 1948 changed all that. This device, which was introduced into everything from computers to guided missiles, sparked the silicon revolution that remade industry in the second half of the 20th century. Gordon E. Moore (see sidebar), chairman emeritus of Intel Corp. and the originator of the scaling law now known as Moore's Law, believes that "silicon intelligence" will evolve to a point when it will be difficult to tell computers from human beings. The computers of today show little sign of intelligence although this trend is already changing. For example, IBM's Deep Blue supercomputer was able to defeat the Russian Grandmaster Garry Kasparov in a chess match.

Semiconductors and Dielectrics

A major materials paradigm shift in the microelectronics industry concerns the replacement of the traditional silicon dioxide/dual-doped polysilicon gate process. This process has been the mainstay of complementary metal-oxide-semiconductor (CMOS) device manufacturing since its inception. The new CMOS gate stack process will likely require nanometer-scale high dielectric constant gate insulators with dual metal gate electrodes. As reviewed in a recent issue of this magazine (see sidebar on page 23), much progress has been made.

Silicon Intelligence

Interface: *Do you have any final comments or thoughts you'd like to share regarding either the past or the future of the semiconductor industry?*

Moore: I can't imagine a more exciting industry to have had a chance to grow up in. The rate of change has been phenomenal and I don't think we're done yet. I think the impact of our new devlopements will go on for a fairly long time. We have a fair ways to go just to continue to push the technology to smaller and smaller things, higher and higher performance. The people who use that technology to make products will then have billions of transistors on a chip to work with, and that gives them almost open-ended possibilities.

—Excerpted from an interview conducted with Dr. Moore in the Spring 1997 issue of Interface

Difficult challenges remain:

- the narrowing of dielectric layer choices and selection of final candidate(s);
- the narrowing of gate electrode material choices and selection of final candidates; and
- the CMOS integration of these disparate materials.

Another consequence of continued device scaling is the difficult challenge associated with the production of abruptly doped ultra-shallow junctions having dopant concentrations in excess of equilibrium limits.

The use of dynamic random access memory modules (DRAMs) for storage capacitors has proliferated because of extraordinary reductions in cost per bit. This has been achieved, in part, by the ability to scale the size of the DRAM storage cell at a rate that is greater than the square of the DRAM half-pitch dimension. The result has been an historic doubling of on-chip bit density every two years. Throughout this period, the storage cell capacitor dielectric has remained SiO_2 or a nitride derivative. However, further aggressive scaling will require a higher dielectric constant insulator. Future-generation DRAM storage cells (stack and trench capacitor designs) will require the implementation of Ta_2O_5 or perovskite-type materials with associated electrode materials that are compatible.

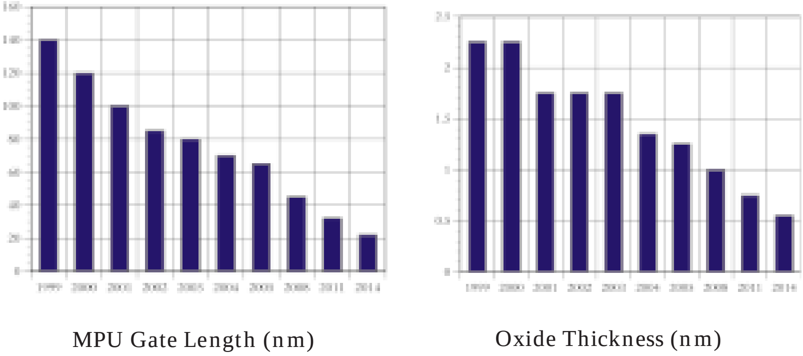


FIG. 2. Projected evolution in the microprocessor unit (MPU) gate length and the dielectric oxide layer thickness, with year. Data from the International Technology Roadmap for Semiconductors, 1999.

"...silicon-based electronic devices could ultimately be replaced by molecule-based counterparts... The challenge is to hook up such molecular wires to perform the same functions as silicon logic gates."

Looking even further down the road, silicon-based electronic devices could ultimately be replaced by molecule-based counterparts. Many experts feel that silicon-based chips will reach a fundamental limit in the not too distant future (as soon as within 15 years), imposed by size limitations, especially if Moore's Law were to hold. On the other hand, a molecule is about a million times smaller than one of today's transistors. Molecule-based logic gates have already been demonstrated, although they are still at a rudimentary stage. The challenge is to hook up such molecular wires to perform the same functions as silicon logic gates. Further, these "nanostructures" must be robust enough to switch repeatedly from one logic gate to another, in order to be practical as a transistor rather than just as a storage device.

Molecular computing is rapidly becoming the Holy Grail in the computer science world. This is because of the potential that molecule-based electronics have for attaining computational speeds several billion times faster than a Pentium III processor chip, and the miniaturization that would lead to the power of hundreds of computer workstations in a space the size of a grain of salt.

Polymers and Carbon-based Materials

Turning to polymeric materials, a major high technology application in the late 1900s has been in the field of photoresists. Global photoresist sales in the 1990s have steadily increased and are in the billion-dollar range. The advent of krypton fluoride and argon fluoride lasers has shrunk attainable linewidths to the 0.1 µm range. Beyond the 157 nm wavelength of a fluorine laser, refractive optics are no longer available. Further resolution increases will come from electron-beam technology or from soft X-rays at 13 nm wavelength. With each successive increment of resolution come new challenges for the photoresist manufacturer. This is because the polymer must be transparent to the incident light used for producing the patterns.

New types of carbon (*e.g.*, buckyballs and buckytubes) comprise another major development in the materials area in the past decade. For example, 1-D nanostructures (*i.e.*, nanowires or nanotubules) of the sort that would be relevant to the development of molecule-based electronics can be derived from these new forms of carbon. The growth of both single-walled and multi-walled carbon nanotubes has been demonstrated. These fascinating materials were recently reviewed in these magazine pages (see sidebar on page 24). Many questions remain regarding fundamental and scientifically interesting issues on the electronic properties of these materials (*e.g.*, coherence of extended states, the role of finite

Nanometer-Scale Dielectrics

...In essence, atomic (nanoscale)-roughness at the Si-SiO_2 interface and structural inhomogeneity are largely responsible for the reliability problem in silicon-based ultrathin dielectrics... Minimization of atomic (nanoscale) roughness at the interface of Si and silicon dioxide is very important for obtaining high quality dielectric films. Processing techniques that can reduce processing temperature and provide a homogenous microstructure resulting in an atomically smooth conductor (poly-Si or metal)/dielectric interface will be used in the manufacturing of reliable circuits. No single processing technique has emerged as a clear-cut winner. Fundamental understanding of the origin of defects is most important for the manufacturing of silicon CMOS circuits based on ultrathin dielectrics.

—Excerpted from the Summer 1999 issue of Interface, *page 22*

size and symmetry breaking, and the consequence of kinks or defects). There is little doubt, however, that carbon-based nanostructures will serve as important building blocks for new generations of electronic, photonic, and optoelectronic materials.

Composites and Ceramics

Paradoxically enough, declining fossil fuel reserves would mean a shift to non-carbon based materials in other technological scenarios. This translates to a major impact in materials utilization and disposal over the long haul, especially from a corrosion and environmental perspective. For example, "green tires," using silica or silica/carbon black as the rubber filler, are already in the market. It is not only the fuel or the type of power source that is likely to change in vehicles, but also the component materials. Already we have seen the steady evolution from a metal-based vehicle of the last century to a plastic/metal composite architecture in today's automobiles.

"Corrosion science will advance dramatically in the next century in order to facilitate the replacement of metals with new conducting materials that can withstand operation in harsh environments."

Corrosion science will advance dramatically in the next century in order to facilitate the replacement of metals with new conducting materials that can withstand operation in harsh environments. For example, the advent of ceramic superconducting materials as contacts and interconnects (instead of metals) has profound implications in corrosion science. On the other hand, how efficacious are the current models for corrosion when applied to superconducting oxides? Mechanistic models for a material or system undergoing multiple corrosion modes do exist, but they have not been sufficiently developed to a level that predictions can be made without resorting to *ad hoc* assumptions or gross simplifications. In particular, we currently lack the ability to design materials that can successfully withstand corrosion in the increasingly harsh environments and more rigid dimensional tolerances typical of tomorrow's technologies.

Sensor Materials

Sensor systems have advanced rapidly during the last century and will continue to do so in the coming century. We have progressed from using mercury thermometers to thermocouples, and from using live canaries to microfabricated sensor arrays. The development of miniaturized chemical and process sensors in the last 20 years has been possible due to advances in microfabrication materials and methods. Microfabricated components are used in chemical sensors ranging from chemically sensitive field-effect transistors (ChemFETs) to optical waveguides and acoustic wave devices.

Materials development in general is central to a successful sensor system in ways that extend beyond just microfabrication. In addition to the materials required for the sensor device structure and packaging, the heart of a chemical sensor is the chemically selective layer itself. This layer may contain material components ranging from metal oxides to polymers or bio-molecules. Many innovative sensing materials will be utilized in the coming century to develop "ideal" sensor systems that meet all sensing requirements.

Challenges in building the ideal sensor include:

- creating an integrated analytical system that constantly undergoes self-diagnostics and self-calibration;
- making it free of matrix interferences;
- enabling it to be sensitive and selective enough to do multiple analytical tasks in a reproducible and reliable manner;
- allowing it to function in harsh environments; and
- giving it a long lifetime.

Certainly, novel sensor materials and architectures must be developed to meet all of these system requirements. In addition, it would be very helpful to use a common sensor platform for a broad range of analytical scenarios without having to design from scratch a system for each sensing application. The use of multiple sensor types and sensor arrays within one device coupled with chemometrics and other modern statistical methods will continue to be developed to address this problem. Integrated sample handling, delivery (*e.g.,* microfluidics), and detection assemblies to optimize analytical sensitivity and selectivity will also emerge, and biological sensor materials (*e.g.*, DNA, proteins) will play an increasingly important role in the future.

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In the near future, the sensor materials that will prevail will be inexpensive and thus disposable. In the longer term, reusable devices and materials will be developed. For example, one can envision that a physical perturbation (pH, temperature, voltage) will be applied to the sensor surface to remove the analyte and restore it to its original condition. Sensing

Carbon Nanotubes

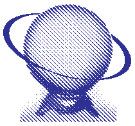
The use of nanotubes, specifically SWNTs, as storage devices for clean fuels (such as hydrogen in hydrogen-based fuel cells) is a topic that is currently attracting a significant amount of interest...One of the niftiest applications that appears to be developing using carbon nanotubes is field emitting displays that are significantly brighter than either cathode ray tubes or Spindt tip based displays... One of the major challenges for the display industry is to develop triode-based displays where individual pixels can be separately addressed with emission and brightness characteristics similar to what has been demonstrated to date. During the course of a very short decade, we have gone from the discovery to seeking methods to producing these materials in commercial quantities, to discovering applications where carbon nanotubes clearly outperform the incumbents.

—Excerpted from the Winter 1999 issue of Interface, *page 36*

materials may even be synthesized *in situ* and on demand, much like our body generates a signal that triggers the generation of antibodies to fight an invasion by a foreign agent such as a virus. We may even witness in the future the development of molecule-based sensors that move through the bloodstream issuing alerts if health problems are encountered. All of these future developments will require a greater understanding of materials properties and molecular interactions to allow the rational design of optimal sensing materials, molecules, and sensor system components.

Processes

We began our story by saying that order-of-magnitude decreases in scale and increases in speed have been possible thanks to advances in both materials and processing improvements in the last century. This is particularly true in microelectronics and the analytical sciences. We expect advances in these areas to continue into the next century as well.



"...synthetic chemists have only recently begun to appreciate the enormity of actually using technology at the molecular level... The day may not be that far away when we have 'nanocomputers'."

Nanotechnology is the craft of constructing things smaller than a few hundred nanometers. Of course, synthetic chemists have long done this for a living but only recently have they begun to appreciate the enormity of actually using technology at the molecular level. Chemists and physicists have recently learned to manipulate atoms around in space, or to even synthesize compounds atom by atom, by using nanometer-sized tips in an AFM or STM instrument. The day may not be that far away when we have "nanocomputers." The guts of such molecular devices will be far smaller than the physical structures (*e.g.,* magnetic domains) that we now manipulate to store information on disk drives. What makes chip making so expensive now is the extreme mechanical precision required. But with chemistry, "chips" (*i.e.,* molecules) can be turned out in readily usable form without the need for mechanical processing, at least in principle. Indeed, nanofab techniques utilizing minuscule robots ("nanobots" in K. Eric Drexler's parlance as described in his book, *Engines of Creation)* not much bigger than specks of dust have been envisioned by think-tanks such as Mitre Corp. in McLean, Virginia.

The field of bioMEMS (*i.e.,* microelectromechanical systems that include biological molecules) is rapidly expanding, from applications related to integrated circuit-chip (IC) technologies to a wide array of biological applications including drug delivery, diagnostics, biotelemetry, and genomics. Manufacture of bioMEMS devices radically differs from IC manufacture because the market demand necessitates a diversity of materials, physical structures, products, and initially lower volumes per product. This has created a need for modular, non-silicon approaches to building inexpensive disposal chemical and biological sensors and systems. Techniques such as electroplating and micromechanical machining have been shown to be extremely powerful, enabling unit processes for bioMEMS and MEMS in general.

For the foreseeable future, at least, silicon-based microelectronics will still have a role. Two major recent advances in this industry have been the development of copper-based interconnects on chips and the move from 8-inch to 12-inch silicon wafers. In both instances, the process of chemical mechanical polishing or planarization (CMP) has made these minor revolutions possible. CMP is being considered for several other electronic applications as well, with the result that this process, and the companies working on it, have witnessed phenomenal growth at a time when the industry in general has been flat, growth-wise.

Critical front-end process challenges beyond 2005 have been identified by the International Technology Roadmap for Semiconductors (ITRS, http://www.itrs.net/ntrs/Pub1NTRS.nsf/):

- metrology and defect inspections—R&D for critical dimension and overlay metrology, and patterned wafer defect inspection for defects < 40 nm;
- gate critical dimension control—development of processes to control minimum feature size to less than 5 nm ($\pm 3\sigma$) and reducing line edge roughness; and
- overlay improvements and measurements—development of new and improved alignment and overlay control methods independent of the technology option.

Challenges also remain in the area of process integration, devices, and structures; again these have been summarized in the ITRS 1999 document; they are:

- overcoming fundamental scaling limits for current device structures—switching drive, noise margin, materials properties, and reliability will limit the performance enhancement obtained from scaling;
- integration choices for system-on-a-chip—cost effective process integration of many functions on single chip; indeed many manufacturers have already envisioned such radically new chip designs (see sidebar below);

Radical New Chip Designs

Three different semiconductor companies are touting a new generation of microprocessor devices... The first, from Texas Instruments Inc., a digital light processor, variously called DLP, DMD or MEMS, is based on light reflection off a grid pattern packed with tiny, tiltable micro-mirrors. Software directs these mirrors to tilt either toward or away from the light lens thousands of times a second. The combination of movements forms images and image contrast... The Sun (Microsystems) chip is designed to handle complex graphics, voice, and video... The new chip is dubbed MAJC (pronounced "magic") and stands for microprocessor architecture for Java computing. Thanks to an unusual design that essentially turns a single chip into a parallel processing system, MAJC chips are claimed to perform complex functions at extremely high speeds... The last new chip on the block, from National Semiconductor, is built around a "system on a chip" concept and comprises seven million transistors. This member of the so-called Geode family is designed to handle computing, graphics, audio, and even digital video... Rumors are that Intel is making a combo chip, code-named Timna, which could appear a year after Geode.

—Excerpted from the Winter 1999 issue of Interface, *page 22*

- design for manufacturability, reliability, and performance—increased complexity includes integration of multi-V_t devices, active devices, high K and high-quality dielectrics for DRAM and non-volatile memory (NVM), and high-quality passive devices;
- low-power, low-voltage, high-performance, and reliable NVM element—this requires voltages that are incompatible with highly-scaled low-voltage devices.

Finally, the need for atomistic process modeling is underlined in ITRS 1999. Regardless of the particular technology direction, it is envisioned that the ability to manipulate and control materials to atomic layer tolerances will be required. However, most device properties are not understood at the atomic level. We are clearly undergoing a transition from the "bulk" process technologies that characterize today's microelectronics industry to tomorrow's molecule-based counterparts.

Analytical Sciences

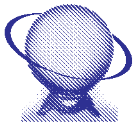
The advent of probes that interrogate at the molecular or atomic level (*e.g.*, AFM, STM, optical spectroscopies) has been a key development, as has been the fabrication methods that allow electrodes (or electrode arrays) to be made with dimensions as small as a few nm ("nanodes"). This, in turn, has opened the door for the deployment of electrochemical technique workhorses such as voltammetry, in real time and *in vivo* scenarios. For example, these techniques have been used for the study of chemical and electrochemical processes that occur in the brain in response to a neurotransmitter drug stimulation. Electroanalytical methods have traditionally suffered in terms of the achievable temporal resolution, relative to their spectroscopic counterparts. The advancements in electrode size shrinkage, measurement circuitry, and data processing that have occurred in the last couple of decades presage a change in this trend. However, it is rather unlikely that we shall see electroanalysis enter the femtosecond domain in the foreseeable future. Instead, electrochemists will continue to discover clever ways to mate electroanalysis with spectroscopic probes and will utilize these hybrid methods in real time and *in situ* analysis scenarios to exploit the sensitivity of optical spectroscopy and the selectivity obtained by combining two complementary techniques.

"Our understanding of electron transfer phenomena will continue to improve, thanks to knowledge gained from the neighboring fields of inorganic chemistry, photochemistry and photophysics, biology, and solid-state chemistry and physics."

Our understanding of electron transfer phenomena will continue to improve, thanks to knowledge gained from the neighboring fields of inorganic chemistry, photochemistry and photophysics, biology, and solid-state chemistry and physics. Synthetic advances will lead to successful man-made analogs of the plant photosynthetic system and enzyme catalysts. The latter will enable our ability to drive and to control, on demand, useful electrolytic and electron transfer processes such as hydrogen evolution reaction, N_2 fixation, and the like.

A Positive Trend for the Next Century

Writers, such as Aldous Huxley in his 1932 novel, *Brave New World*, and John Naisbitt in *High Tech High Touch* (1999), have warned of the dangers of a society enslaved by technology. Barring a few hiccups here and there, we have managed the use of technology in a prudent and beneficial manner. It can be argued that, contrary to the picture painted in the above literary works, individual freedom and the quality of life have improved in the technologically more advanced societies. Technology—stemming from basic scientific advances—has played a more important role in this regard, especially in the last century, than either politics or economics. There is every reason to expect that this positive trend will continue into the next century, especially as we become even more sensitive to the adverse effects of technology (such as environmental pollution, software bugs, and genetically altered food) and are taking the necessary steps to ameliorate them.



"...technology will continue to play a pivotal role in the next century—a period that will be shaped by spectacular and very rapid advances in the basic sciences, information technology, biotechnology, energy research, and materials science and processing."

In concluding this retrospective and predictive exercise, it is our belief that technology will continue to play a pivotal role in the next century—a period that will be shaped by spectacular and very rapid advances in the basic sciences, information technology, biotechnology, energy research, and materials science and processing. The future indeed looks bright. ■

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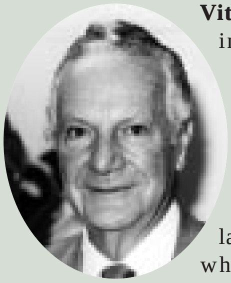
Landmark Discoveries of the Past Century...

What qualifies for a landmark discovery? Is it new theory, new technology, or a new material? It is all the above, but more importantly, it is an "enabling" development that altered the course of history or profoundly influenced the way we live. On a more specialized level, it changed the way we do electrochemistry and solid-state science and technology. Any compilation, by its very nature, is intrinsically subjective but few would argue with the importance of many of the discoveries listed below. For the sake of brevity, we list these discoveries in three categories in no particular order. However, such a classification into neat little boxes is completely arbitrary. We have also identified some of the people who have brought these developments into being. Here then is our own list of the all-time greats of the 20th century.

Device/Technology

- electrolytic capacitor
- glass electrode for pH measurements
- alkaline fuel cell
- lithium primary battery
- silicon solar cell
- operational amplifier
- integrated circuit chip
- transistor
- personal computer
- polarograph
- potentiostat/galvanostat
- laser
- fiber-optic cable, fiber-optic amplifier, and wavelength division multiplexing
- World Wide Web (Internet)
- wireless communication technology (*e.g.*, cellular phone)
- electrosynthesis (e.g., Baizer-Monsanto process, chlor-alkali, synthesis of adiponitrile)
- Clark oxygen electrode
- scanning probe microscopies
- combustible gas sensor
- lithography and nanofabrication

Herbert H. Dow—He graduated from the Case School of Applied Science in 1888. He was an assistant professor of chemistry and toxicology at the Huron Street Hospital College in Cleveland, and spent his spare time in developing a process for the extraction of bromine from brine. The Midland Chemical Company, started by Dow in 1890, was the first to use electrolytic apparatus to commercially manufacture a chemical other than metal. The Dow Chemical Company was organized in 1897 for the manufacture of chlorine and bleaching powder. He received the Perkin Medal in 1930 and died later that year. He was a charter member of ECS and a memorial student achievement award was established in his name by the ECS Industrial Electrolysis and Electrochemical Engineering Division. The award, first given in 1991, was made possible by a gift from The Dow Chemical Company Foundation. *(Photo courtesy of the Chemical Heritage Foundation.)*



Vittorio de Nora—Born in Altamura, Italy in 1912, he received the degree of mechanical and electrical engineering from the R. Politecnico of Milan. He received a PhD in chemical and metallurgical engineering in 1937 from Lehigh University. He carried out and directed research at universities and in laboratories of industrial companies, which led to the design, engineering, and construction of electrochemical plants throughout the world. Some of his major contributions were in the manufacture of chlorine and in the development of dimensionally-stable electrodes, which have revolutionized the electrochemical and electrometallurgical industries. The Society's Vittorio de Nora Award was founded in 1977 by Dr. de Nora and the Diamond Shamrock Corporation.

Edward Weston—He was born in England in 1850 and came to the U.S. in 1870. Employed by the American Nickel Plating Company, he was responsible for many improvements in the nickel plating art. In 1888, he formed the Weston Electrical Instrument Company in Newark, New Jersey for the purpose of manufacturing electrical instruments. He invented the Weston Cadmium Cell, which became the voltage standard throughout the world. He also developed a system of incandescent electric lighting. He received many honors, including an honorary doctor of science, and was made an Honorary Member of ECS in 1926. One of the Society's Summer Fellowships, given to assist a student during the summer months, was named for Weston. *(Photo courtesy of the Chemical Heritage Foundation.)*

Manuel M. Baizer—Born in 1914, he received his PhD in 1940 from the University of Pennsylvania. In the early 40s, he taught instrumental chemistry at Brooklyn College, and was a research associate for the National Defense Research Committee of the University of Pennsylvania. He moved to Monsanto Company in 1958, where he eventually became a Distinguished Fellow. Dr. Baizer served as Chairman of the Organic and Biological Electrochemistry Division (1975-1977). He made significant contributions to the science and technology of organic electrochemical synthesis. The Manuel M. Baizer Award was established in 1992 in memory of his many contributions to the field of organic electrochemistry and to the Society.

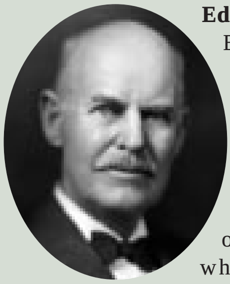
Ed. Note: Thank you to Dennis R. Turner, Society Historian and 2000 Vittorio de Nora Award winner. His work on the biographies of Society notables helped in the preparation of this list.

...in Electrochemistry and Solid-State Science and Technology

Materials

- silicon
- plastics and synthetic rubber
- polymer membranes (*e.g.*, Nafion, dialysis membranes)
- superconductive ceramics
- new (synthetic) forms of carbon
- high-strength metal alloys
- stainless steels
- dimensionally-stable anodes
- conductive glass and polymers
- metal-carbon composites

Leo H. Baekeland—Born in 1863 in Ghent, Belgium, he received his ScD (1884) from Ghent University. The University of Pittsburgh conferred on him an honorary doctor of chemistry in 1916. He came to the U.S. in 1889 and later became a research chemist and honorary professor of chemical engineering at Columbia University. His research work included physical, general, industrial, and organic chemistry; the synthesis of resinoids and intermediate bodies resulting from the action of phenols upon formaldehyde; photographic processes; and electrical insulation. One of Dr. Baekeland's inventions made the news in 1995. The heat shield on the 1995 Jupiter probe was a phenolic resin based on phenol and formaldehyde. The first phenolic resin, Bakelite, often used in pot handles, was invented in 1909 by Dr. Baekeland, the same year he was ECS President.



Edward G. Acheson—Born in 1856, Edward G. Acheson was a charter member and early president of the Society (1908-1909). He worked for Thomas Edison at the Menlo Park, NJ laboratory, where he experimented on a conducting carbon that could be used in electric light bulbs. On his own, he discovered silicon carbide, which he called "carborundum." It was found to be a better abrasive than any other known substance except diamond. In 1895, a plant was built in Niagara Falls and soon carborundum was competitive with other abrasives. Acheson received many honors and awards including the Perkin Medal and an honorary Doctor of Science degree. In 1928, Acheson provided funds to establish an eponymous award. Acheson himself was the first recipient in 1929, and over the years, the Acheson family has continued to maintain this prestigious award.

Theoretical Developments

- photoelectric effect (Einstein)
- electron transfer (Dogonadze, Marcus, Hale, Hush)
- superconductivity (Bardeen, Cooper, Schriefer)
- semiconductor/metal and semiconductor/semiconductor junction behavior (Bardeen, Shockley, Brattain, Schottky, Mott, Hall, Read)
- electrode/solution hydrodynamics (Levich)
- double-layer theory (Grahame)
- semiconductor electrochemistry (Gerischer)
- thermodynamics of electrochemical processes (Nernst)*
- mechanistic aspects of organic electrochemistry (Saveant, Lund, Baizer)
- corrosion science and engineering (Pourbaix, Wagner, Evans, Uhlig)

*Nernst's work (leading to the famous equation bearing his name) appeared in 1889 but because of its far-reaching importance is included in this post-1900 compilation.

Rudolph A. Marcus—Born in Canada in 1923, Rudolph A. Marcus earned his PhD in 1946. He moved to the U.S. in 1949, motivated by his interests in theoretical chemistry, and to complement his experimental work as a postdoctoral fellow at the National Research Council of Canada. While attending the 1992 meeting of ECS in Toronto, Dr. Marcus was informed that he was the recipient of the Nobel Prize in Chemistry. The basis of the Prize was Marcus's fundamental work on electron transfer reactions, which are among the most important of chemical processes; and his work on rates of electron transfer has far-reaching implications.

Carl Wagner—Born in Leipzig, Germany, he obtained his PhD from the University of Leipzig in 1924. In 1934, he went to the Polytechnic Institute of Darmstadt, advancing to full professor. He served as editor of *Zeitschrift fur physikalische*. In 1949, he joined the department of metallurgy at MIT as a visiting professor. He became head of the Max Planck Institute at Goettingen in 1958. He was recognized internationally for his outstanding contributions to the theory of oxidation and the tarnish of metals. His theory was the most important advance in corrosion science since the proposal of the electrochemical theory of corrosion in aqueous media. The Carl Wagner Award was first presented in 1981, and was established to commemorate a dedicated teacher, the Society's first Palladium Award winner, and his outstanding scientific achievements.

David C. Grahame—Born in 1912, he received his PhD from the University of California, Berkeley, in 1937. He was an instructor in chemistry at Berkeley, and moved to Amherst College in 1942, becoming a full professor in 1953. He published a large summary in *Chemical Reviews* of his classic work on the electrical double layer. This work outlined the fundamental principles that govern electrical double layer formation at metal-solution interfaces. He took an active part in arranging symposia for the Physical Electrochemistry Division. He was an inspiring teacher of physical chemistry. He was only 46 years old and holding a Guggenheim Fellowship, when he died in 1958.