Daniel C. Tsui

1998 Nobel Prize in Physics Goes to Tsui, Störmer, and Laughlin

Daniel C. Tsui, Arthur Legrand Doty Professor of Electrical Engineering at Princeton University and a member of the Materials Research Society, shares the 1998 Nobel Prize in Physics with Robert B. Laughlin of Stanford University and Horst L. Störmer of Columbia University and Bell Laboratories, Lucent Technologies for discovery of a new form of quantum fluid with fractionally charged excitations.

Tsui and Störmer made the discovery in 1982 in an experiment using extremely powerful magnetic fields and low temperatures. Within a year of the discovery Laughlin had succeeded in explaining their result. Through theoretical analysis he showed that the electrons in a powerful magnetic field can condense to form a kind of quantum fluid related to the quantum fluids that occur in superconductivity and in liquid helium. Events in a drop of quantum fluid can afford profound insights into the general inner structure and dynamics of matter. According to the Royal Swedish Academy of Sciences which awards the prize, the contributions of the three laureates have led to further understanding of quantum physics and to the development of new theoretical concepts of significance in many branches of modern physics.

Tsui, Störmer, and their co-workers performed experiments on the quantum Hall effect in the semiconductor gallium arsenide, using even lower temperatures and more powerful magnetic fields than have been utilized previously. To do so, they created a unique environment, a trap in which to restrain electrons on a two-dimensional plane. This was done by sandwiching two dissimilar semiconductor wafers—gallium arsenide on one side and gallium aluminum arsenide on the other. Electrons accumulated at the interface between the two semiconductors and were tightly confined. Next, the researchers cooled the electron trap down to a tenth of a degree above absolute zero. To their great surprise, they found a new step in the Hall resistance which was three times higher than last reported by German physicist Klaus von Klitzing in 1980, for which he received the Nobel Prize in Physics in 1985. Klitzing's discovery is known as the integer quantum Hall effect in which the electrons move only in certain circular paths, the basic sizes of which are determined by the magnetic field. The various steps turn out to show how many of the smallest paths are entirely full of electrons. The steps occur at resistance values that do not depend on the properties of the material but are given by a combination of fundamental physical constants divided by an integer. Tsui, Störmer, and their colleagues subsequently found more and more new steps, both above and between the integers. All the new step heights can be expressed with the same constant as earlier but now divided by different fractions. For this reason the new discovery was named the fractional quantum Hall effect.

A year after the discovery of the fractional quantum Hall effect, Laughlin theorized that the low temperature and the powerful magnetic field compel the electron gas to condense to form a new type of quantum fluid. Since electrons are most reluctant to

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condense, they first combine with the flux quanta of the magnetic field. Particularly for the first steps discovered by Tsui and Störmer, the electrons each capture three flux quanta, thus forming bosons.

Apart from its superfluidity, which explains the disappearance of Ohmic resistance at the Hall resistance steps, the new quantum fluid proposed by Laughlin has many unusual properties. One is that if one electron is added the fluid will be excited and a number of fractionally charged quasiparticles created. These quasiparticles are not particles in the normal sense but a result of the common dance of electrons in the quantum fluid. Laughlin was the first to demonstrate that the quasiparticles have precisely the correct fractional charge to explain Tsui and Störmer's experimental results. Subsequent measurements have demonstrated more and more fractionally charged steps in the Hall effect, and Laughlin's quantum fluid has proved capable of explaining all the steps found experimentally.

Tsui, born in Henan, China, received his PhD degree in physics in 1967 at the University of Chicago. He joined the faculty at Princeton University in 1982. Störmer, born in Frankfurt, received his PhD degree in physics in 1977 at Stuttgart University, Germany. He has supervised the Physical Research Laboratory at Bell Labs from 1992 to 1998, then joined the faculty at Columbia University this year. Laughlin, born in Visalia, Calif., received his PhD degree in physics in 1979 at the Massachusetts Institute of Technology and has been a professor of physics at Stanford University since 1989. Among other awards, Tsui and Störmer in 1984 and Laughlin in 1986 received the Oliver E. Buckley Prize from the American Physical Society and the 1998 Medal of the Franklin Institute for their work associated with the fractional quantum Hall effect.

Molecular Dynamics Studied with Use of Miniaturized Shock Waves

A procedure for investigating materials under extreme conditions using laser-driven shock waves has been developed at the University of Illinois. The miniature shock waves, safe and efficient, can be used to study fundamental processes at the molecular level.

To generate their miniature shock waves at high repetition rates, professor of chemistry Dana Dlott, postdoctoral research associate Selezion Hambir, and graduate student Jens Franken use a tabletop picosecond laser system with a laser pulse energy of 0.1 mJ and a multilayered shock array target which consists of a substrate (glass), a thin layer of the material of interest (e.g., anthracene, which is a model system for molecular solid materials; or high explosives such as RDX, TATB, or NTO; or biomaterials

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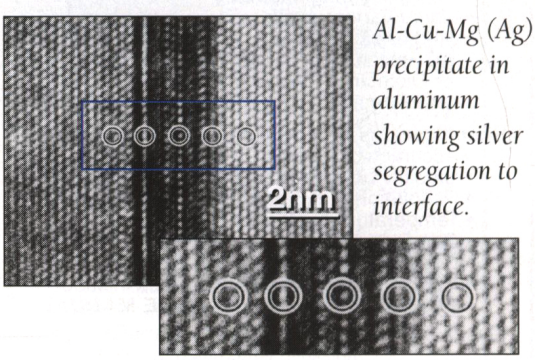
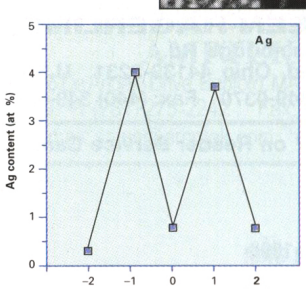


Al-Cu-Mg (Ag) precipitate in aluminum showing silver segregation to interface.



Data courtesy of Dr. James M. Howe, Department of Materials Science & Engineering, University of Virginia, U.S.A.

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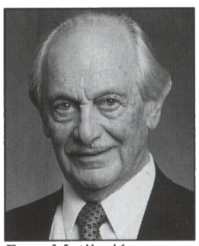
such as the heme protein myoglobin), and a clear polymer cover layer, usually PMMA (poly methyl methacrylate).

First, the laser pulse—focused to an intense spot about 100 μm in diameter — is aimed at the thin outer layer of the target. This "shock generation" layer consists of a polymer, PMMA, doped with a near-IR dye (e.g., IR-165 for a Nd:YAG laser) and an energetic binder. The researchers sometimes put some explosives such as RDX in the shock layer to get a bigger shock. The molecules absorb the laser energy and explode, sending a shock wave through the sample below. The target is then moved slightly by a motorized platform and the process is repeated at up to 100 times per second. The resulting shock waves, which have a duration of a few nanoseconds, are called "nanoshocks."

Dlott said, "Nanoshock pulses can suddenly drive the material to extreme conditions of high pressure, high temperature, or large mechanical deformation. These phenomena can then be probed by optical or vibrational spectroscopy, which allows molecular-level behavior to be investigated."

Describing the research at the American Chemical Society meeting in Boston in August, the researchers said that the ultrafast nature of the nanoshock technique makes it a powerful tool for studying the molecular dynamics of complex systems. For example, nanoshocks produce a very fast temperature jump that can initiate a thermochemical reaction. The shock wave rapidly compresses the sample, causing intense heating. Then, as the material springs back, it cools quickly on a subnanosecond time scale. According to Dlott, "It thus becomes possible to obtain spectra of materials that react or decompose too quickly to study by conventional means. Large organic and biomolecular systems, which have never been studied at high temperatures and pressures, are now within reach." The researchers offer an animated presentation of how the nanoshock experiment works at website http://dlottgroup.scs.uiuc.edu/group/.



Egon Matijević

University of Zagreb Honors Matijević for Work in Colloid and Surface Science

Egon Matijević of Clarkson University and a member of the Materials Research Society received an honorary degree this summer from his alma mater, the University of Zagreb in Croatia, recognizing his half-century of accomplishments in colloid and surface science, especially monodispersed colloids and their applications. At the ceremony on June 25, Matijević delivered a special address on his "Fifty Years of Research in Very Fine Particles: Science and Art."

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Matijević's research has helped shape the modern field of colloid and surface science. His techniques for preparing fine particles, uniform in size and shape, have applications in products like the capacitors used in microelectronics, magnetic memories, and the ceramics used in electronic components.

Having earned both a PhD degree in chemistry (1948) and a Dr. Hab. in physical chemistry (1952) at the University of Zagreb, Matijević came to Clarkson in 1957 following a year as a research fellow at Cambridge University in England. Instrumental in the founding of the Institute of Colloid and Surface Science at Clarkson University, he served for many years as its director. He also played a vital role in the emergence of Clarkson's Center for Advanced Material Processing and its recognition by New York State as a Center for Advanced Technology. The author of more than 500 scientific papers, he has delivered numerous plenary and keynote lectures in many countries, including the Faraday Discourse at the Royal Institution in London.

Structure of Dental Alloys Analyzed by XPS-XRD Combination

Researchers at Ohio State University, Material Interface, Inc., and the University of Wisconsin—Milwaukee have employed a combination of x-ray photoelectron spectroscopy (XPS) and x-ray diffraction (XRD) to discover new information about the structure of oxide layers on dental alloys. William A. Brantley, professor of restorative dentistry, prosthodontics, and endodontics, said, "Each technique alone will only tell you one thing, but together they can give some special results."

The researchers reported in the June issue of the *Journal of Materials Engineering and Performance* that the combination of XPS and XRD revealed information about the complex near-surface structures of the oxidized palladium alloys that dentists commonly use for conventional restorations and implant-supported crowns and bridges. Such restorations typically consist of a porcelain crown fused to a metal base.

Brantley said he and his colleagues applied the dual x-ray technique to this critical oxide layer because scientists know very little about its structure, especially for the complex palladium dental alloys which contain many different elements. The first technique, XPS, reveals the oxidation state of atoms on the surface and the concentration of atoms belonging to different oxidation states. The second technique, XRD, takes advantage of the crystal lattice makeup of the alloys. Each region of unique composition and structure in a crystalline material has its own characteristic set of x-ray reflection peaks, so scientists can use the peaks to identify the regions within the material.

The researchers examined two different oxidized palladium alloys, and XRD revealed that the position of the peaks did not match those previously published in the scientific literature. When the researchers applied the XPS technique to the same alloys, they found that some of the palladium oxide had chemically bound with water, most likely from the residual atmosphere found in the dental vacuum furnace used to fire the porcelain.

Brantley said, "Once the XPS information was available, we could interpret the XRD results to mean that the hydrated palladium oxide wasn't at equilibrium, or was experiencing stress in the oxidized layer. That's what changed the position of the XRD peaks."

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From the use of XPS, the researchers also discovered microcrystals of gold and copper within the oxide layer, which also altered the XPS peak energies but were too small to detect with traditional XRD.

In general, oxide layers on alloys grow in one of two ways: down into the surface of the alloy, or out into the air. XPS revealed that strong oxide layers on palladium-copper-gallium alloy grow out into the air, whereas the weaker oxide layers on the palladium-gallium alloys grow down into the alloy surface.

"We think that explains why the porcelain adherence is superior for the palladium-copper-gallium alloys [than for gold alloys]," said Brantley. "We can use this information to design new alloys that will bond to porcelain even better."

Oxygen Ions Help Evaluate Electrically Charged Plasma

One of the problems to producing fusion in a controlled manner has been the difficulty of systematically studying the plasma. A research team led by Yitzhak Maron of the Weizmann Institute's Particle Physics Department has developed a method for definitively determining how electricity flows through plasma. This study provides information about the way hot and dense plasmas are formed.

To produce controlled fusion in the laboratory, scientists strike the plasma with a magnetic field generated by an electric current, which contracts the plasma to a small volume and keeps it hot and dense. Maron's team, which included graduate students Gilad Davara, Lev Gregorian, and Eyal Kroupp, evaluated the electric current flowing through the plasma using the spectrum of the light emitted by this charged gas. Because plasma is so hot and dense, its spectral lines usually become blurred. The scientists solved this problem by introducing oxygen ions into the plasma, which produce a neat and clear spectral line that is less disturbed by heat and density.

While the lifespan of plasma is <1 μs, Maron and his team were able to measure the current and track its distribution for every nanosecond. They found that when the current first entered their 4 × 1.5-cm roll of plasma, it flowed on the outside of their sample. They then measured how far it penetrated into the roll when the plasma contracted. These measurements also enabled the scientists to determine the velocity of the plasma's particles, which was found to reach 100 km/s (360,000 km/h). The experiment was conducted at about 10^5°C.

By knowing the behavior of the electric current, scientists can determine the exact distribution of its magnetic field. Since this field is the driving force behind plasma compression, such measurements may help researchers understand how to condense plasma more effectively in their quest for harnessing nuclear fusion as a controlled energy source.

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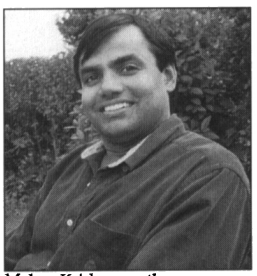
Mohan Krishnamurthy

Mohan Krishnamurthy of Michigan Technical University died on August 26, 1998 in a drowning accident at the age of 33. Known to everyone in the field of electronic materials simply as Mohan, he had already achieved a great deal for someone so young, and all who knew him predicted even greater things for the future.

Mohan obtained his BTech degree from the Indian Institute of Technology in his native Madras in 1986 with high honors. He then came to Arizona State University where he completed his masters in 1988, and his doctorate in 1991 both in materials science and engineering, with Dean Jacobsen and me as advisors. After passing his course work with a perfect GPA, he presented his research proposal fluently to his committee; as I recall, the only substantive question asked was how he was going to decide between the six alternative theses he had presented in the 90 minutes allowed for the examination.

This was a young man in a hurry, one of the most focused and impressive I have been privileged to work with. He fully justified this promise, working closely with postdoc Jeff Drucker (now at the University of Texas—El Paso), producing an excellent thesis on Ge/Si(001) growth using a range of microscopy and diffraction techniques, especially developing *in situ* UHV-SEM studies with the MIDAS instrument at ASU. This work was published in the *Journal of Applied Physics* **69** (1991) p. 6461 and in several Materials Research Society proceedings in 1990–1992. Mohan also found time for sport and hiking in Arizona, and was a natural leader and infectiously good-humored role model within the Indian community at ASU.

He then moved to the University of California—Santa Barbara to work with Pierre Petroff and others in QUEST, producing a string of papers on InGaAs and AlGaAs semiconductor superlattices as well as other materials of interest in modern electronic materials. His paper with Leonard et al. in 1993 (*Appl. Phys. Lett.* **63**, p. 3203) is one of the most widely cited in this competitive field; Krishnamurthy mastered all the necessary experimental techniques, and was instrumental in pursuing the ideas behind the formation of coherent strained islands and their potential use as quantum dots and wires.

After a brief return to ASU to work with Jim Mayer and David Smith on GeSiC alloys, Mohan obtained his assistant professorship at MTU in 1994, and was given tenure this summer as an associate professor. In Houghton, he was on a steeply rising curve when the tragic accident occurred during one of his few afternoons of time-out. He was launched with a five-year National Science Foundation (NSF) Career award in 1996, and had research support into the next century from NSF, Office of Naval Research, DARPA, and other governmental and industrial grants and contracts. He was playing a full role within MRS as a symposium organizer initially with the 1997 Spring Meeting. He was organizing Symposium V: Epitaxial Growth-Principles and Applications at the 1999 Spring Meeting; this role will now be taken by Tom Pearsall. At the time of his death he had several keen young graduate students and was highly appreciated by both students and faculty at MTU for both his research and his teaching.

My last contact with him was a typical 1998 e-mail exchange on August 24. He had visited in June, and I got some wonderful photos of him in our yard, very upbeat and pleased with life. I sent him the pictures, with jokes about a career in modeling sunglasses should all else fail, and he e-mailed back all chirpy, proud of his recent paper with student X. Deng about modeling Ge/Si quantum dot experiments (*Phys. Rev. Lett.* **81** [1998] p. 1473), referring to ideas we had worked on together at ASU and to projects we might consider in the future. He leaves his widow Swaran and many friends and colleagues in the United States, the Indian subcontinent, Singapore, and elsewhere with a great sense of loss. Such things shouldn't happen, but unfortunately sometimes they do. We are all the richer for Mohan's participation in our lives. The electronic materials community has tragically lost one of its brightest rising stars.

JOHN VENABLES

Science Publishes Special Issue on Materials Science

The August 14 issue of *Science* features four articles and a special news section on how creating defects can have major implications for the future of electronics and materials science.

In one article, "Defects in Semiconductors: Some Fatal, Some Vital," H.J. Queisser of Max-Planck-Institut für Festkörperforschung in Stuttgart, Germany and E.E. Haller of the University of California—Berkeley, review several of the major ways in which defects affect the performance of semiconductors. In some cases researchers grow pure semiconductor crystals and then dope them with foreign atoms. Alternatively, some defects occur naturally within a semiconductor crystal, and researchers must find ways of controlling, or exploiting, these defects.

H. Ohno of Tohoku University in Sendai, Japan, in "Making Nonmagnetic Semiconductors Ferromagnetic," discusses advances made in merging the capabilities of nonmagnetic semiconductors, like silicon, with those of magnetic materials. The results could be used to engineer instruments that could perform mass storage and process information at the same time. Ohno shows how researchers have magnetized a nonmagnetic semiconductor by

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adding an impurity to the material.

In "The Roles of Structural Imperfections in InGaN-Based Blue Light-Emitting Diodes and Laser Diodes," Shuji Nakamura of Nichia Chemical Industries in Tokushima, Japan, describes the development of a type of light-emitting diode (LED) that takes advantage of certain semiconductor defects. An LED gives off light when electric current flows through it. Both CD players and communications systems involving optical fibers use LEDs. However, applications for LEDs have been limited because, until recently, few materials emitted blue light efficiently. For example, a CD player uses a red laser to read information stored in tiny crevices on the surface of a CD. A laser with a shorter wavelength such as blue could access smaller crevices so that a CD could hold several times as much information. The author reports on progress in creating LEDs that emit blue light.

Demand is increasing for powerful communications media that can transmit information at high bandwidth capacities. Currently, information travels through glass optical fibers in the form of light waves. A.F. Garito, J. Wang, and R. Gao at the University of Pennsylvania summarize, in "Effects of Random Perturbations in Plastic Optical Fibers," their own progress in improving bandwidth capacities in settings where the fibers must bend and turn sharply by substituting plastic optical fibers for glass. In this case, minute defects in the optical fibers help coordinate the signals as they travel, which increases the fibers' bandwidth capacity.

The news section features articles on carbon nanotubes and the role that defects play when materials crack.

Combination of TiO_2 and $Ni(OH)_2$ Films Creates a Photochromic Material

While studying an electrode consisting of thin transparent films of nickel hydroxide and titanium dioxide, researchers at Lawrence Berkeley National Laboratory and the University of California—Berkeley discovered a photochromic material. Chemist Robert Kostecki said, "We were looking for an additive to improve the performance of rechargeable alkaline batteries which use nickel hydroxide electrodes, so we added the titanium dioxide film to the nickel hydroxide film in an attempt to inhibit unwanted oxygen gas formation. I wanted to see what would happen when I exposed it to ultraviolet light. When we did this, we saw that the electrode, which had been nearly transparent, darkened. This result indicated that the combination has potential use as either a photochromic device or an electrochromic device, or both."

Electrochemical reactions driven by light in the ultraviolet spectrum produce the photochromic behavior. As reported in the July issue of the *Journal of the Electrochemical Society*, when light strikes the titanium-nickel sandwich, electrons from the $Ni(OH)_2$ layer flow to the TiO_2 film. The II-$Ni(OH)_2$ oxidizes into a form of higher nickel (III-Ni and IV-Ni) oxides. As it does, what was a transparent film gradually darkens into shades of gray and black. When the light is blocked, the reaction reverses itself. Full coloration of the prototype device from transparency to its darkest state requires about 10 minutes.

Frank McLarnon, also of Berkeley Lab, said, "Several problems have prevented the large-scale fabrication of photochromic and electrochromic devices. They include the lack of adequate reversibility (switching back and forth from transparency to a colored state), instability of the material over the long term, and high cost."

This material addresses certain problems. "One advantage is that it turns gray on exposure to light," said Kostecki. "Also, you can deposit it on any type of substrate—glass, plastic, or ceramic—whether it is conductive or not. Current photochromic materials are expensive, whereas electrochromic materials require a conductive substrate. Finally, titanium dioxide and nickel hydroxide are easy to produce and very inexpensive, and are widely used in ceramics, pigments, catalysts and other products." The material's ability to store information in a binary form—transparent or dark, representing zeros and ones—or to encode data as levels of gray, also makes it a candidate for display-panel and memory-device applications.

The research team still must solve some problems. Kostecki said, "The material darkens mainly in response to the ultraviolet light. We need to modify the film so it will respond efficiently to the solar spectrum. Also, we need to develop technology to produce TiO_2 and $Ni(OH)_2$ films which are as uniform and transparent as possible."

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Unlimited Growth of Anodic Oxide Films Produced on Valve Metals

Researchers at Kemet Electronics Corp. in Greenville, South Carolina have reported in the September issue of *Electrochemical and Solid State Letters*, the production of nonporous films of unlimited thickness on the so-called "valve" metals (e.g., Ta, Ti, Al) at relatively low dc voltage. Uniform oxide films of approximately 20 μm in thickness have been grown on tantalum with an applied voltage of 20–30 V dc. According to Brian Melody, R&D Group Manager at Kemet, this represents an increase of 10–20-fold over the film thickness possible with conventional anodizing technology. He said that they have obtained similar results with other valve metals, such as aluminum and titanium.

After immersing a 2.5-cm wide Ta foil coupon in a glycerin-based anodizing solution and subjecting the material to 20 V at various temperatures (from 125°C to 180°C) at various lengths of time under 24 h, the researchers found that the non-thickness-limited anodic film growth begins to occur within 145–150°C, and only with the anodizing solutions containing <0.1% water. In another part of the experiment, the researchers held the Ta coupon at 30 V for 24 h in a 10 w/w % dibasic potassium phosphate solution in glycerin at 150–175°C. The film grew to about 19-μm thick, which, according to the report, "is the equivalent to anodizing a film to approximately 9500 V under traditional, 85°C anodizing conditions."

The researchers prepared electrolytes containing one or more of other solvents, including poly(ethylene glycol) 300, poly(ethylene glycol) 8000, triethanolamine, sucrose, *N*-hydroxyethyl-2-pyrrolidone, mannitol, pentaerythritol, 1,2-butanediol, 1,4-butanediol, and 2,3-butanediol. They found unlimited thickness growth with glycerin and mannitol, but not with hydroxyl-rich compounds. Based on these results, the researchers said that, for unlimited growth to occur, a minimum of three adjacent carbon atoms must bond to the hydroxyl groups. The behavior of unlimited growth is apparently dependent on an environment in which tantalum ions in the surface of the oxide bond to oxygen ions produced at the oxide surface; in other words, oxygen ions enable the Ta to move from the metal substrate into the oxide film. □

Corrections

The diamond electrodes on the cover of the September 1998 issue of *MRS Bulletin* were made by Heidi B. Martin of Case Western Reserve University. In figure 3 in the article by G.M. Swain, A.B. Anderson, and J.C. Angus (*MRS Bulletin*, September 1998, p. 58), "Conduction-Band Maximum" should be "Conduction-Band Minimum."

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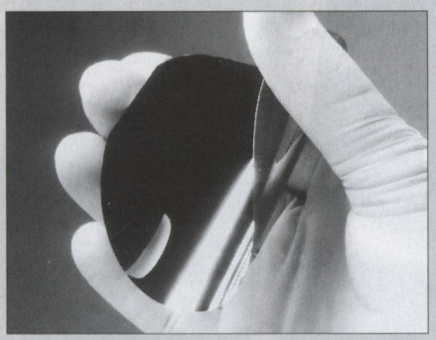
"But still try—for who knows what is possible?"

– Michael Faraday



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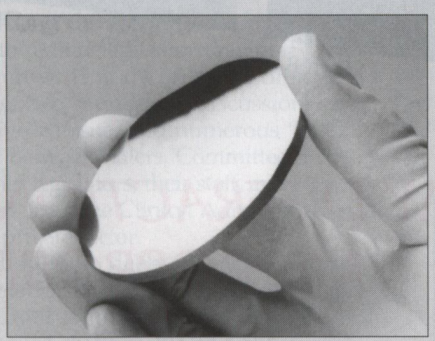

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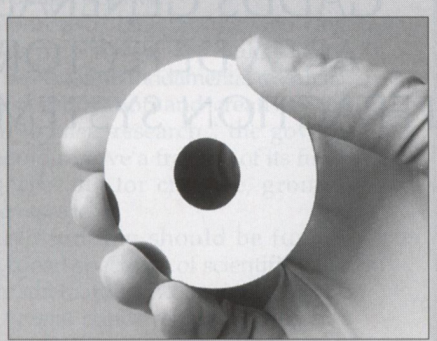

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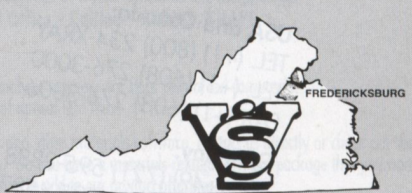
When it comes to preparing engineered silicon products, we have frequently stated (with tongue in cheek), "if we can't make it, you don't need it!"

In the final analysis, we are most eager to **IMAGINE**, to be **CHALLENGED**, and to **TRY**. At Virginia Semiconductor, Inc., we think of the possibilities—not the limitations. Those who know us now expect nothing less; why shouldn't it be that way in our service to you?



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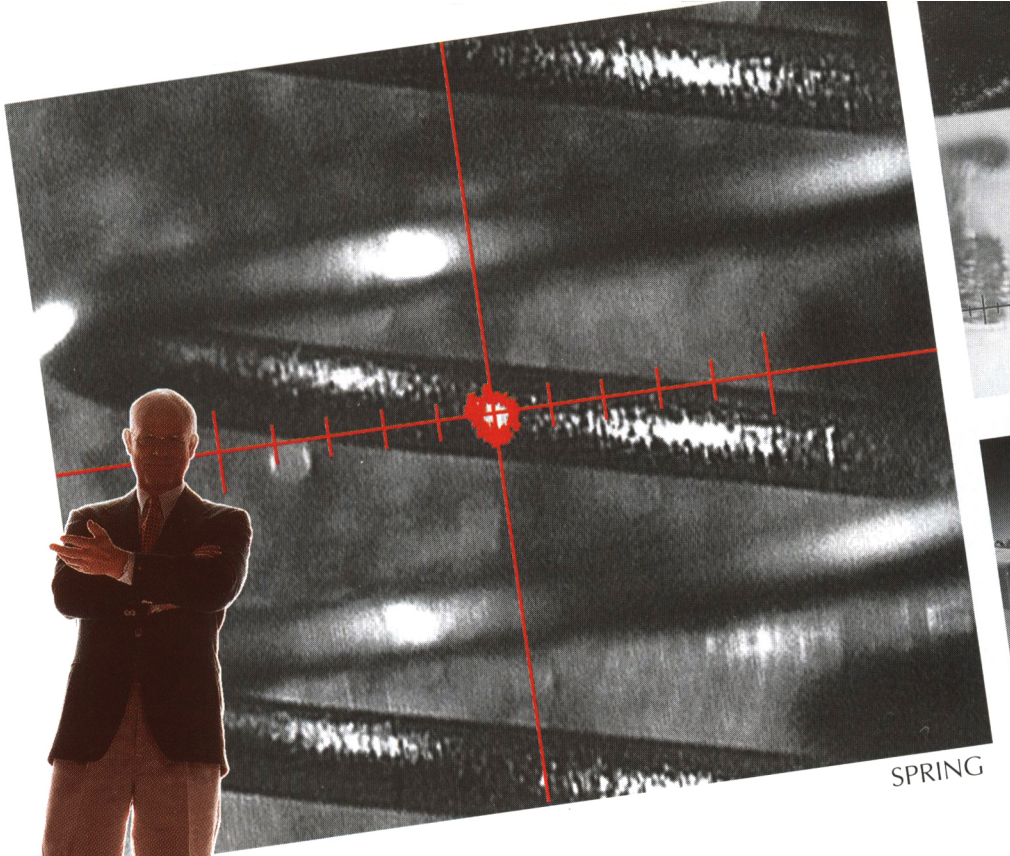

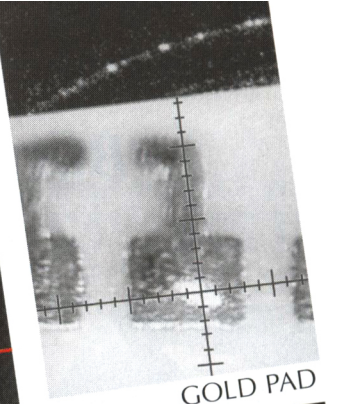

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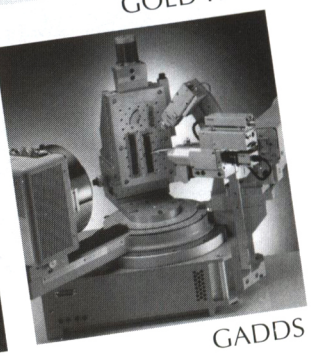

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