A Century of Electrical Engineering and Computer Science at MIT, 1882–1982

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Chapter 11

The Laboratory for Insulation Research: Arthur R. von Hippel

When Arthur R. von Hippel came to MIT in the fall of 1936 at the invitation of President Compton, he brought with him a rich background for the contributions he would make in what he was to call molecular science and molecular engineering. As an undergraduate and graduate student at the University of Göttingen, where his father was a professor of criminal law, he witnessed the new discoveries of Wolfgang Pauli, Werner Heisenberg, and Erwin Schrödinger as these young physicists brought quantum-mechanics corrections to Niels Bohr's famous model of the atom. But von Hippel, being of a practical turn of mind, joined Göttingen's Institute for Applied Electricity, where in 1924 he was awarded the Ph.D. degree, summa cum laude, for a thesis entitled "The Theory and Investigation of the Thermomicrophone." He developed measuring instrumentation for the design and testing of this device.

As assistant to Professor Max Wien in Jena (1924–1927) he was asked to investigate the magnetic properties of sputtered metallic films, which assignment led him to look deeply into the sputtering process itself and to publish four papers on the subject in *Annalen der Physik.* After a year as Rockefeller Fellow in Physics at the University of California, he lectured at Jena (1928–1929) and at Göttingen, where he investigated the mechanism of electrical breakdown in gases, liquids, and solids in Professor James Franck's Physikalische Institut (1929–1933). An initial paper with Professor Franck, entitled "Electrical Breakdown and Townsend's Theory," was followed by his own series of three papers on breakdown in solid insulators in *Zeitschrift für Physik.* During this productive period he saw that the breakdown mechanism could best be revealed through the study of material having ordered structure, such as single crystals. Concentrating on the alkali-halide crystals, which could easily be grown in his laboratory, he discovered "avalanche breakdown" in solids, observing the destruction paths proceeding backward from anode to cathode in specific crystallographic directions. He also discovered that sparks building up in gases from positive electrodes had a quite different pattern from those at negative electrodes.

Political events in Germany were to push his investigations elsewhere. Unwilling to swear allegiance to Hitler, he and his wife, Dagmar, Franck's daughter, left Germany for a stay of 18 months (1933–34) in Istanbul, Turkey, where he became professor of electrophysics. A decisive period in his career followed (January 1935 to September 1936), spent as guest professor at the Niels Bohr Institute of the University of Copenhagen. Professor Bohr became one of von Hippel's heroes, as Franck had been at Göttingen.

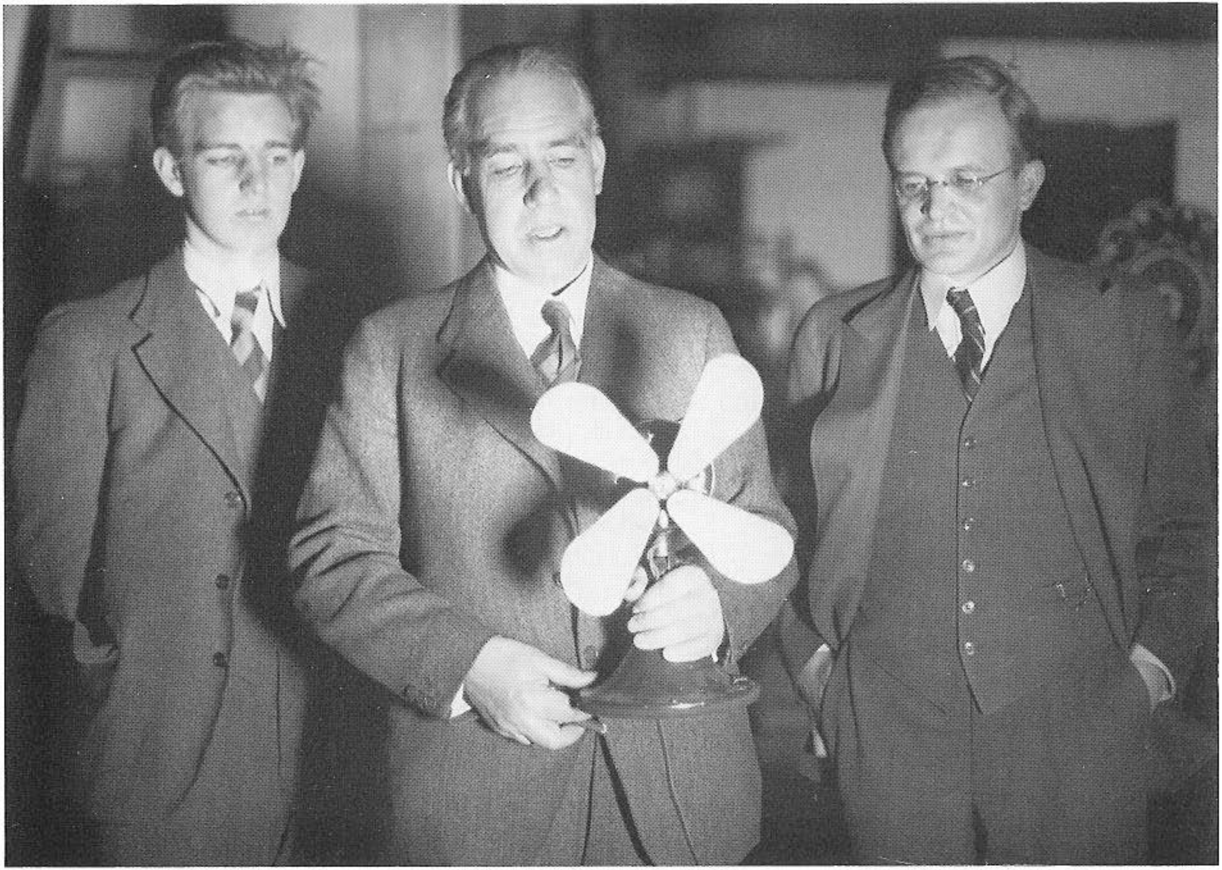
Then President Compton personally invited von Hippel to come to MIT; a physicist with such a background, Compton believed, could likely make important contributions to the Department of Electrical Engineering.

Initiation into the EE Department

Von Hippel's arrival at MIT in September 1936 was hardly auspicious. The department was not at all aware of his earlier work or of his plans, and no preparations had been made to accommodate his research. He was assigned a small windowless room in the basement of Building 10 while instructor Gordon Brown, in charge of the research laboratories, rearranged the space in Room 10-395, inside which an enlarged Room 10-371 (the former cinema integraph room) was made available in November. The instruments and other equipment that von Hippel had brought from Europe were set up in this laboratory. Other equipment was soon added: a vacuum system, a 20,000-volt DC source, and special devices that von Hippel designed and built locally. He was immediately helpful in the final phases of the doctoral theses of H. Y. Fan "(Transition from Glow Discharge to Arc") and Dean A. Lyon "(Electric Strength of Extremely Thin Insulating Films"), presented for June 1937 degrees. Two significant researches during von Hippel's first year at MIT were on the breakdown of glass under high-voltage stress and on the emission of electrons from metals into solid insulators.

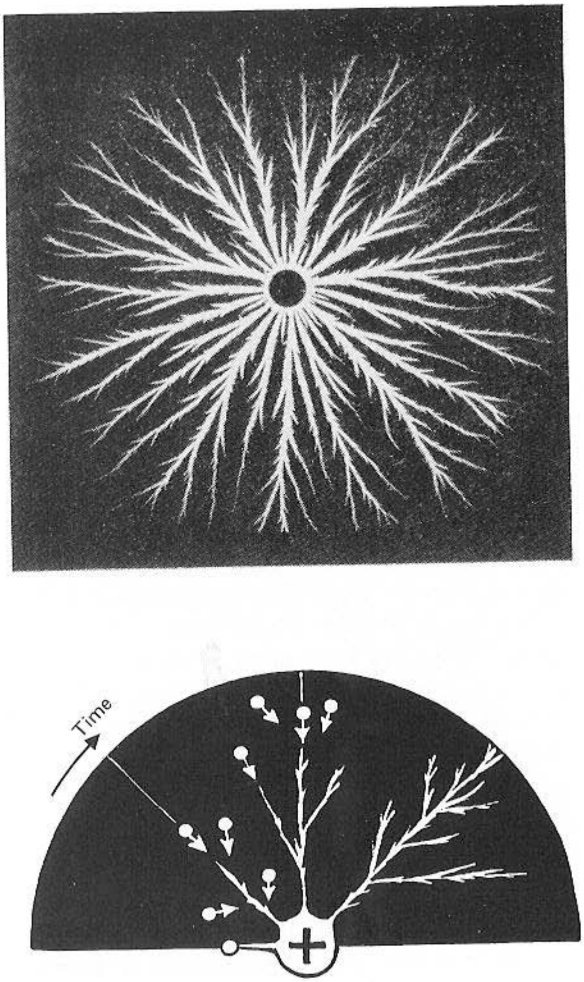
By May 1937 the MIT community was convinced that von Hippel's revolutionary ideas could indeed make a significant contribution to electrical engineering; Professor Moreland decided to have him take over, starting in the fall of 1937, undergraduate subject 6.26, Insulation, thereby relieving Professor Moon to devote most of his attention to the new Course VI-B, Illuminating Engineering. Here in 6.26 von Hippel introduced his new point of view, showing that the dielectric properties of materials were determined by the behavior of electrons, ions, atoms, and molecules. A new graduate subject, 6.64, Electric Insulation, emphasizing major advances in insulation, was inaugurated by von Hippel in the spring of 1938. So attractive were his research and teaching that already in 1937–38 he supervised three master's theses.

Research Reports for November 1939 reported, "Recognizing the situation and the promising start that had been made, the Institute some time ago inaugurated a *laboratory for insulation research* in the Department of Electrical Engineering. In development since November, 1937, this laboratory bridges between physics and electrical engineering by attacking the problems of insulation from the atomistic standpoint." As von Hippel's research expanded, it embraced staff and students in physics and chemistry as well as in electrical engineering. Not only did this Laboratory for Insulation Research (LIR) thrive and expand



Arthur R. von Hippel (*right*) with
Niels Bohr and Bohr's son.

for more than three decades, but von Hippel's book *Molecular Science and Molecular Engineering* brought profound and significant changes to the materials technology of those years. Young men of unusual ability came to work with von Hippel. For example, Julius P. Molnar, who later became executive vice-president of Bell Telephone Laboratories and subsequently president of Sandia Laboratories, did his physics thesis, "The Absorption Spectra of Trapped Electrons in Alkali-Halide Crystals," with the materials, apparatus, and guidance in LIR. Others investigated the initial stages of electric breakdown in gases through a study of Lichtenberg figures; examined the propagation of electrons in single crystals as a wave phenomenon; and studied with von Hippel the importance of order versus disorder by comparing crystals with glasses, extending this work to study the effect of temperature, the action of frequency, and the transition from insulator to semiconductor and metal.



Positive Lichtenberg figure and its growth pattern.

Wartime Activities

Von Hippel had an opportunity to demonstrate his anti-Hitler position when, in the early days of World War II, the president of the International Telephone and Telegraph Company sought aid in producing selenium rectifiers. The company's facilities in Germany had been lost, and its attempt to reproduce them in New York had been catastrophic—about 90 percent of the production had to be thrown away. By studying the phase transitions of selenium from the red insulating to the gray metallic form, and the rectifying action of the boundary, von Hippel and his coworkers designed a method to produce good rectifiers rapidly by electroplating. The production time was shortened from a thermal anneal of two days to an electrolytic formation in twenty minutes. They also studied the making of selenium photocells and their spectral response, and retained for MIT the patent right to convert solar into electric energy by this method.

In September 1941 von Hippel became a citizen of the United States—just three months before the Pearl Harbor attack pushed America into World War II. During the war LIR assumed responsibility for the development and measurement of radar dielectrics, as well as for the initiation of their proper manufacture and application. The laboratory had to create measurement techniques and equipment to determine the dielectric constant and loss in all kinds of materials as a function of temperature and of frequency, from DC through the microwave region. The decimeter and centimeter ranges were practically unexplored territory. New types of standing-wave equipment, such as the MIT Coax instrument, had to be developed and their manufacture arranged, as well as their distribution to American and Allied government and industrial laboratories. After the war the Coax instrument was manufactured commercially; it remains today a standard tool for the measurement of dielectric properties at centimeter wavelengths. The classified reports called "Tables of Dielectric Materials" are still a major reference in the field. They were prepared under the leadership of William B. Westphal, who joined LIR after receiving his bachelor's degree in 1942. As leader of the Dielectric Measurements Group, he established an international reputation in dielectric measurement and continued his work in this area until 1980.

Polymers like polystyrene and polyethylene were quite new at that time, having been used as filler materials for rubber tires and for some household items; they had to be upgraded to low-loss radar dielectrics and their useful temperature range extended by additive agents, since the Navy persisted in running radar cables through the boiler rooms of battleships. Many other materials—plastics and rubber, ceramics and glasses, single crystals and polycrystalline materials—were needed and had to be made in the laboratory or by industry.

In developing "high dielectric-constant ceramics," von Hippel discovered the ferroelectricity of barium titanate ($BaTiO_3$) and used this material to produce high-voltage capacitors and ceramic delay lines. Studies on these dielectrics led to the application of dielectric heating for rapid wood curing. The making of selenium photocells pulled LIR into war research on infrared photocells of the thallous sulfide type. Classified LIR wartime reports and subsequent publications summarize these developments.

In the course of the war it became clear that a close liaison was required between LIR and the government agencies responsible for the procurement and proper application of dielectric materials. Thus the laboratory joined with the Army, the Navy, and the War Production Board to form the War Committee on Dielectrics. The committee met in Washington once a week during the later war years, and after mutual trust had been established, it successfully handled a number of emergency situations. This relationship led to an Army–Navy–Air Force three-service contract with LIR to start peacetime materials research.

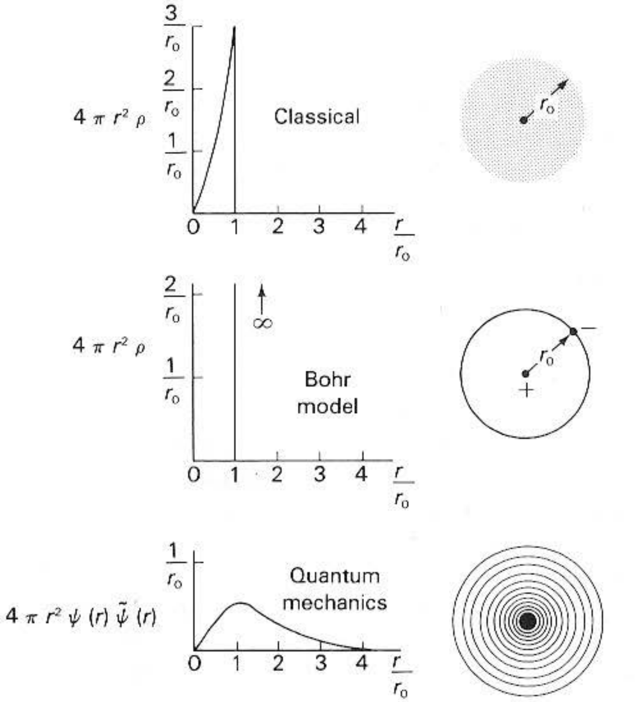
The New Peacetime Program

During the war von Hippel was a member of the Radiation Laboratory (see chapter 13); but he kept his LIR organization intact, so that when the Radiation Laboratory disbanded in late 1945 LIR was in a position to continue its research. It was at this juncture that von Hippel perceived clearly the challenge of transforming the whole field of materials research, using as a basic approach his book *The Molecular Designing of Materials and Devices.* The idea was to create new materials to order by synthesizing them out of the basic building blocks at the molecular level. This is molecular engineering. The understanding of the building blocks and their interrelationships is molecular science. In his postwar program von Hippel was more and more insistent on understanding the behavior of materials as they occurred in nature, on understanding how the observed phenomena happen and how they can be influenced by molecular means.

Von Hippel wrote, “The molecular engineer starts his synthesis of materials from *atoms* as the fundamental building stones.” Bohr had originally modeled the atom as a positively charged nucleus with electrons rotating around it as the planets move around the sun. Bohr was quick to understand the quantum mechanics of Heisenberg, Schrödinger, and Pauli, and his “orbits” became atomic “orbitals.” Orbitals were conceived as shells of probability distributions of electron positions, solutions to the Schrödinger wave equation, concentric about the nucleus. The outer electrons determine the valence or combining properties of the atom when the outer shells are not filled. Many physical properties of various elements have been learned from their atomic structure.

The next, more complicated, building block beyond the atom is the molecule. When two hydrogen atoms unite to form a hydrogen molecule, new forces come into play. Each atomic electron is no longer confined to its atomic orbital, but the two electrons of the molecule share an orbital relationship with the two nuclei. As von Hippel says, “Intelligent construction of the next set of building blocks, the molecules, requires insight into the rules of interaction between atoms: why certain molecules prove stable and others unstable, why certain combinations form voluntarily and others only under coercion, why certain partnerships between atoms lead to small, saturated molecules of defined structure and others grow into macrostructures by continuous addition.” These relationships were thoroughly understood and taught to von Hippel's students and colleagues.

The study of atomic and molecular structure led into the investigation of other kinds of structure. For example, in the early 1950s manufacturers of transistors

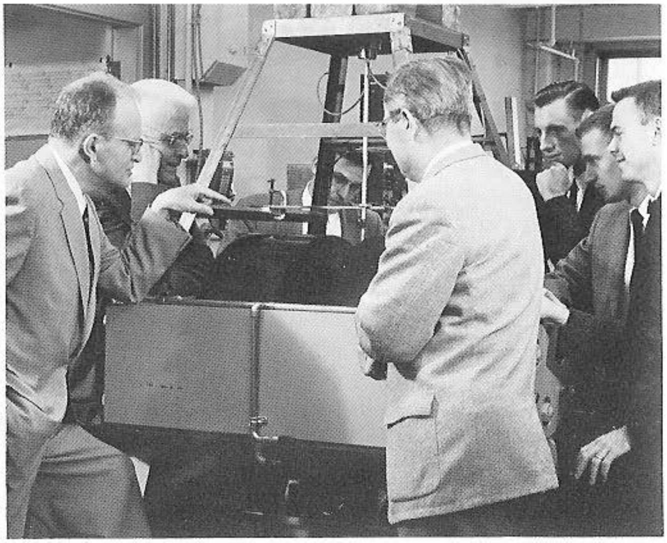


Three models for electron charge distribution in the hydrogen atom: the classical model, an electron cloud of uniform density; the Bohr model; the quantum-mechanics model (normalized to unit electron charge).

were having problems in producing pure crystals of germanium and silicon. It was at this time (1952) that von Hippel brought Alexander Smakula (Göttingen Ph.D. 1927) into LIR. Smakula, a specialist in growing single crystals, contributed to solving the crystal-growing problem. (Incidentally, Smakula had been the inventor of the antireflection coating for optical lenses so widely used today in camera lenses.)

The molecular approach brought great insight into the electromagnetic behavior of all kinds of materials. Electrical conduction in single (nearly pure) crystals, in semiconducting (doped) crystals, and in metals was studied in depth. Electrical conduction and breakdown in gases, including natural lightning phenomena, were investigated in the laboratory and in the field. Lichtenberg figures gave testimony to the sequence of events in such phenomena. These studies led to an understanding, not only of the disruptive and destructive qualities, but also of the useful qualities of gaseous breakdown—as in neon, mercury, and sodium lamps, as well as in the thyratron and ignitron tubes used as control devices and switches.

Not only did von Hippel build an interdisciplinary staff of chemists, physicists, metallurgists, and electrical engineers; he also built an international one by inviting scientists from abroad to spend extensive periods in LIR. Studies of ferroelectric materials were strengthened and expanded with the coming of Berndt Matthias, a postdoctoral fellow who had done research on ferroelectricity at the Swiss Federal Institute in Zurich. The electrical, electromechanical, optical, and domain properties of barium titanate single crystals provided topics for a number of doctoral theses and led to important publications, among them a paper by von Hippel in the *Reviews of Modern Physics* in 1950. Walter Merz, also from the Swiss Federal Institute, contributed to the ferroelectric research. Matthias and Merz, after leaving the laboratory, went on to establish worldwide reputations as leaders in the field of ferroelectricity and superconductivity.



LIR group discussing the operation of a magnetometer. *Left to right:* von Hippel, Stanley Kingsbury, David J. Epstein, Perry Miles, Robert Hunt, Archie MacMillan, Alexander Smakula.

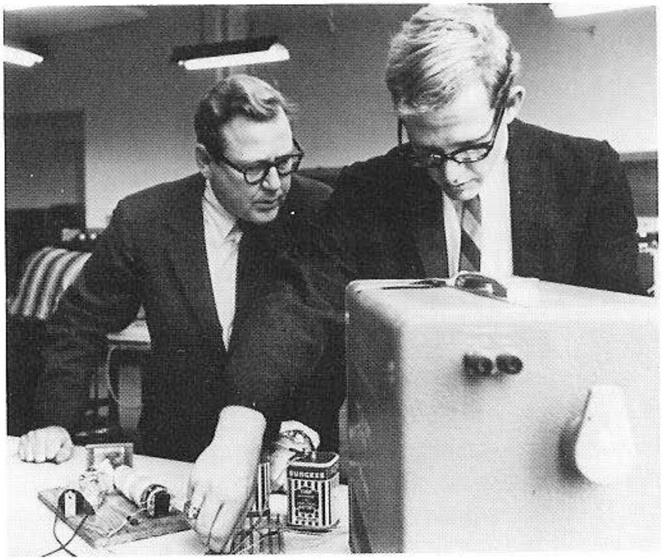
David J. Epstein, who was to develop the undergraduate core curriculum subject 6.08, Molecular Engineering, during the Gordon Brown era (chapter 19), entered MIT as a graduate student in 1947 with a research assistantship in LIR. He received the master's degree in 1949 and the Sc.D. in 1956, with a thesis entitled "Magnetic Lag in Ferrites," both the S.M. and Sc.D. theses being supervised by von Hippel. Although Epstein became von Hippel's leader in magnetic materials, he had a comprehensive grasp of the whole field of molecular engineering, as evidenced in his classroom and laboratory teaching of materials engineering to undergraduates. The educational laboratory dealt with the role of materials in modern devices: junctions in semiconductors, transistors, dielectric and magnetic amplifiers. Forrester's coincident-current magnetic-core memory for digital computers used ferrites as core materials (see chapter 17).

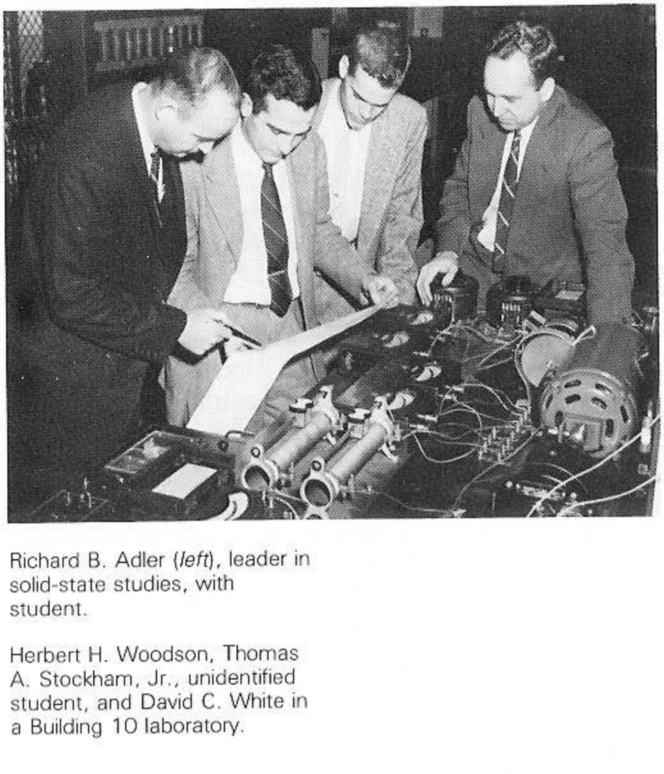
Richard B. Adler, a member of the staff in the Research Laboratory of Electronics (RLE) since 1946 and of the department's faculty since 1949, was strongly influenced in his subsequent transistor research and teaching by von Hippel's molecular point of view. Adler became the first leader of the new Lincoln Laboratory's solid-state and transistor group, which he headed as long as it remained housed on campus in RLE (1951–1953). Leading up to the extensive use of transistors in digital computers, Adler supervised, for example, several master's theses on transistor magnetic-core drivers as these were being built in the Digital Computer Laboratory, and he pioneered (with S. J. Mason, C. R. Hurtig, and W. E. Morrow) in the development and use of a new nonlinear circuit model for point-contact transistors.

Adler's leadership in transistor theory and applications gave him an excellent background for helping Gordon Brown in his program to broaden the field of energy conversion. To revitalize the electric power field, teachers had to make it attractive to bright young people. Given the success of science during World War II, and the strong component of science in the new semiconductor materials and devices field, the bright young people were certainly drawn in those directions. Thus, it was argued, if electric power could be upgraded into a more fundamental and broader discipline than merely the study of transformers, transmission lines, and rotating machines, and if this more general discipline could involve the new semiconductor materials and the rising molecular engineering point of view, then surely it would be irresistible to this new generation.

In addition to Brown's encouragement, Professor Pierre Aigrain of the University of Paris pointed out that the efficiency of thermoelectric converters had been drastically underrated by Lord Kelvin. Moreover, the semiconductor technology brought about by advances in the transistor field offered real promise of making significant improvements in the physical properties of semiconductors by using the strategies of molecular engineering to make them more effective thermoelectric converters.

In the late 1950s a small group studying thermoelectric processes and materials was set up in RLE, cooperating with a French group at the Laboratoire Centrale des Industries Electriques in Paris. Aigrain participated in the RLE group and led the one in Paris. Somewhat later, the Energy Conversion Laboratory was set up in Building 10 by Professors David C. White and R. B. Adler to develop thermoelectric conversion as a practical means of electric power generation and refrigeration. Another member of the team was Paul E. Gray, whose doctoral thesis on the dynamics of thermoelectric machines (1960) was supervised by White. Aigrain continued to conduct related research in France and visited the MIT project regularly, giving inspiration and guidance. Major American participants from outside MIT were the Navy and corporations like Westinghouse and General Electric. Very





Richard B. Adler (*left*), leader in solid-state studies, with student.

Herbert H. Woodson, Thomas A. Stockham, Jr., unidentified student, and David C. White in a Building 10 laboratory.

intensive work in this field was also carried on in the Soviet Union during these years.

For eight years, beginning in 1960, Adler served as technical director of the Semiconductor Electronics Education Committee (SEEC). An international university- and industry-sponsored educational development effort, headed by Professor C. L. Searle with other MIT participation by Professors P. E. Gray, A. C. Smith, and R. D. Thornton, the SEEC developed seven volumes of textbooks, a number of pedagogical laboratory experiments, and four educational films, in an integrated package. The SEEC was designed to bring the solid-state electronics revolution, which had started with the invention of the transistor in 1948 at Bell Telephone Laboratories, firmly into the electrical curricula of the universities, worldwide—a task in which it was largely successful.

The period 1958–1966 saw the parallel development of the Center for Materials Science and Engineering from the seeds sown by LIR, RLE, the Energy Conversion Laboratory, and Lincoln Laboratory (see chapter 17); it saw, too, the involvement of more young people in issues concerning the generation of electric energy than had been involved in the conventional field of electric power for many previous years. Ultimately, however, it became clear that "energy conversion" was not a particularly helpful unifying concept, because the underlying principles of electromechanics, magnetohydrodynamics, and conversion from heat to any other form of energy are quite different in character. Revitalization of the electric power field for the long term had to await the emergence of solid-state power electronics, cheap computation, and alternative fuels, so that radical changes in the whole system—as a system—could begin to take place in an economic environment of expensive imported petroleum.

After about five years of von Hippel's postwar program, he believed the time had come to share the new molecular approach with workers outside MIT. In his book *Dielectrics and Waves* he set forth the "macroscopic" phenomena involved in dielectric measurements and then presented the new "molecular" point of view.[1] His "conviction that scientists, engineers, manufacturers, and users of dielectrics should learn to speak each other's language and appreciate mutual problems, failures, and advances was the driving impulse which led to the Summer Session Course of LIR at MIT in September 1952." The lectures, given by specialists from government, industry, and LIR, were reviewed and edited into a book, *Dielectric Materials and Applications*,[2] published in 1954. Problems were "brought into the limelight which could stimulate much fruitful new activity." The book closed with about 150 pages of a first public issue of the "Tables of Dielectric Materials." Other MIT investigators—John G. Trump, Dudley Buck, and William N. Papian—contributed chapters (see chapters 10 and 17 of this volume).

Again in 1956 von Hippel organized a summer session group to share experiences. The lectures were again edited into a book, *Molecular Science and Molecular Engineering*, and published in 1959.[3] Von Hippel says, "My colleagues, each one in his own field, have added the depth of understanding and experience demanded by our universal theme." Out of 22 contributors besides von Hippel, we mention a few who are involved in our present historical review: Epstein contributed a chapter entitled "Ferromagnetic Materials and Molecular Engineering"; Adler wrote a survey of semiconductor diodes and transistors; Smakula's chapter was "Growth and Perfection of Single Crystals."

Now the bandwagon was really rolling. But to get an honest appraisal of insights and capabilities achieved, LIR sponsored in 1963 a summer course entitled "The Molecular Designing of Materials and Devices." There were 82 registered participants and 37 lecturers, covering subjects from atoms and molecules to the design patterns of the most complex materials and devices. From abroad came Helen D. Megaw of the Cavendish Laboratories in Cambridge; Carl Wagner, director of the Max Planck Institut für Physicalische Chemie in Göttingen; Hendrik A. Klasens and Gert W. Rathenau of Philips Eindhoven; Heinz Raether of Hamburg University; and Alfred von Engel of Oxford University; a scintillating array of experts from American government, American industries, and MIT were present as well. The resulting book, also entitled *The Molecular Designing of Materials and Devices*, was published by the MIT Press in 1965.[4]

The field of materials research was examined critically during the 1958–59 academic year by Professors von Hippel, Adler, Nicholas J. Grant of Metallurgy, and John C. Slater of Physics, leading to the development of a program of financial support for a consolidated MIT effort. In the preamble to von Hippel's laboratory report for January 1961, he mentions a federation of four EE laboratories as an intermediate step toward a truly interdepartmental Center for Materials Science and Engineering. These were his own LIR; the Computer Components and Systems Group in Building 10, directed by Ewan W. Fletcher; the Energy Conversion Laboratory already mentioned; and the Materials Applications Section of the Electronics Systems Laboratory (ESL) under James G. Gottling.

The 1961 report of President Julius A. Stratton announced that in June the U.S. Advanced Research Projects Agency (ARPA) had negotiated a contract to supply a large sum that would be incorporated into the larger program of the Center for Materials Science and Engineering, already operating in the laboratories of several departments in anticipation of the new building that was to house the center.

The building, the largest constructed since the original MIT complex, was finished in 1965; in 1966 it was named the Vannevar Bush Building. Although the larg-

Vannevar Bush Building, home of the Center for Materials Science and Engineering. The concept of research "centers" in which the interests of different specialists could be federated has been growing in importance at MIT during the past two decades. The building for the Center for Materials Science and Engineering, completed in 1965, has brought together scientists and engineers from many departments and research groups at MIT.

est departments in the center were Metallurgy and Materials Science, Electrical Engineering, and Physics, the new facilities were made available to the Institute-wide community. The research groups (crystal physics under Smakula, magnetics under Epstein, magnetic spectroscopy under Perry Miles, ceramics under George Economos) and three other LIR groups moved to the new building with von Hippel's blessing. Von Hippel continued to carry on considerable research in his Laboratory for Insulation Research until 1980, when his laboratory (then in Building 38) was completely terminated. The Arthur R. von Hippel Reading Room in the Bush Building was "dedicated to Arthur von Hippel, Institute Professor, pioneer in interdisciplinary research and materials science and engineering," on November 19, 1973.

Mildred S. Dresselhaus, director of the Center for Materials Science and Engineering from 1977 to 1983.

Many materials problems that relate to electrical, electronic, and magnetic devices have been solved in the Center for Materials Science and Engineering. The materials thus considered by members of the department have ranged widely, including, for example, the lead salts PbTe, PbSe, and PbS, used for thermoelectric energy conversion; more recently, a variety of oxides selectively doped with rare-earth and transition-metal ions that function as sensitizers and activators for photo- and cathodo-luminescence; and amorphous semiconductors such as are used in xerographic copying, vidicon tubes, and electronically alterable memories.

The Center for Materials Science and Engineering enables about 40 professors and their research groups from several academic departments to work together interactively, sharing central facilities. The directors of CMSE have been Professors Robert A. Smith (Physics, 1960–1968), Nicholas J. Grant (Materials Science and Engineering, 1968–1977), Mildred S. Dresselhaus (Electrical Engineering and Computer Science, 1977–1983), and J. David Litster (Physics, 1983 to the present).