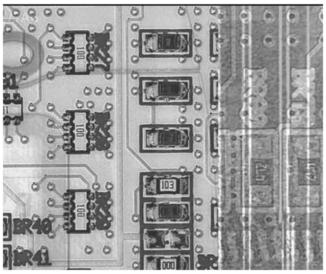
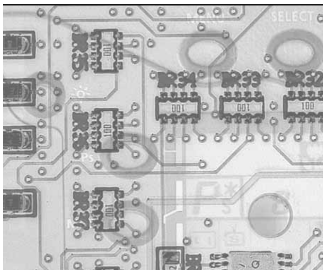
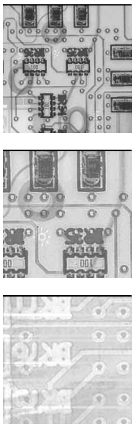




PART ONE

HISTORICAL INTRODUCTION



CHAPTER 1

BEFORE MOORE'S LAW: LINEAGES OF CHEMISTRY AND ELECTRICITY

Arnold Thackray

Moore's law offers fundamental insight into the most transformative technology of the past half century: silicon semiconductor electronics. By reflecting on Moore's law and its contexts, we may gain a greater understanding of this technology and its effect on our lives. Why such a reflection should be offered by the Chemical Heritage Foundation (CHF) and developed through a symposium that took place in Philadelphia requires some explanation.

CHF's symposium was held in May 2005 to mark the fortieth anniversary of Gordon Moore's original publication of Moore's law in an article (reprinted in this primer and titled "Cramming More Components Onto Integrated Circuits"). May 2005 also coincided with the fiftieth anniversary of the event that brought the silicon to Silicon Valley: the establishment of the Shockley Semiconductor Laboratories. Why would CHF, an organization devoted to the history and heritage of the chemical sciences and technologies, undertake a symposium on the history of silicon electronics? Simply put, silicon semiconductor electronics is the most recent development in a centuries-old history of the interconnection between chemistry and electricity.

There is a strong lineage of important research centered on the electrical and chemical properties of materials and their interconnections, tracing back to at least the eighteenth century. Gordon Moore and his contemporaries who authored the silicon revolution are the most recent generation of researchers in this line. Indeed, silicon semiconductor electronics are created by the chemical and physical manipulation of silicon and other materials to produce desired electronic functionality. The silicon revolution is the most recent of several consequential episodes in the long engagement of the chemical with the electrical.

But why Philadelphia as the location for the symposium? What connections does this place have with the subject? CHF is located in Philadelphia because of the city's central role in the history of the chemical enterprise in America. The story stretches from the heyday of Benjamin Franklin's scientific fame to the heady era in the middle of the twentieth century that gave rise to silicon electronics.

Benjamin Franklin (1706–1790) and his electrical activities are famous. Franklin, of course, made the whole territory of electricity very much the subject of conversation and speculation, and Philadelphia was central to that community of inquiry. Among Franklin's scientific contributions was his discovery of Joseph Priestley, a young dissenting protestant minister in England, whom Franklin persuaded to venture into the new field of electrical investigations and thereby into a career as a scientific researcher. Priestley would go on to earn a reputation as one of history's greatest chemists and eventually emigrate to Franklin's Philadelphia and Pennsylvania.

Priestley (1733–1804) is a member of the second generation of our lineage, along with Luigi Galvani (1737–1798) and Alessandro Volta (1745–1827). Franklin's influence most directly reached this second generation through his relationship with Priestley. Indeed, Priestley's first scientific book was titled *History and Present State of Electricity* and included original experiments. In this book, Priestley delivers a remarkably prescient statement about the relationship between the science of chemistry and the science of electricity: "CHYMISTRY [is] the great field of knowledge for the extension of electrical knowledge: for chymistry and electricity are both conversant about the latent and less obvious properties of bodies; and yet their relation to each other has been but little considered." As we approach the 250th anniversary of this statement, one might say that Gordon Moore and his successors are bringing to fruition this relationship of chemistry and electricity.

The first great event in the sequence that followed Priestley's proclamation was Luigi Galvani's work with frogs' legs some twenty-five years later. Galvani, by connecting a strip made of iron and brass with each metal touching a frog's leg, made the leg twitch, even though the frog was obviously not alive. The observation prompted Galvani to posit an "animal electricity," a form of electrical fluid responsible for the activity of muscles.

As is usually the case in science, Galvani's claim was greeted with skepticism, particularly by his contemporary Allesandro Volta. Volta was convinced that Galvani's results had nothing to do with the inclusion of animal matter and everything to do with the two types of metal. Volta undertook a similar experiment connecting two dissimilar metals through a brine solution, leaving out the frogs' legs and thereby produced current electricity and the first battery.

With Volta's work a new world had been entered. Current electricity became a great sensation. Here was electricity produced by chemical means. An indication of how great a stir Volta's work caused is evidenced by Volta's personal summons to demonstrate the electric current phenomenon to Napoleon Bonaparte, who later made him a count.

For the next generation of researchers, Volta's results led to the emergence of a relatively "big science" approach to the exploration of the relationship of chemistry with electricity. Humphry Davy (1778–1829) grasped the true potential of what Volta had initiated. He had the insight that if one battery cell is good, then hundreds must be better. This enabled him to decompose chemical substances that had resisted earlier efforts, thereby discovering new chemical elements such as sodium and potassium.

Davy's discoveries caused a great sensation. The pace of discovery began to quicken. Davy, like Franklin, also contributed greatly to science by recognizing the research talents of a contemporary. In Davy's case, the individual was an impecunious young Michael Faraday (1791–1867), who first became Davy's assistant and eventually his scientific successor as professor of chemistry at the Royal Institution in London. By connecting electricity to magnetism, it was Faraday who would attain the next great milestone in our understanding of electricity. Moreover, Faraday built on Davy's work and codified the laws of electrolysis—the decomposition of chemical substances by electricity. In so doing, he introduced the most familiar terms of both electrochemistry and electronics: ion, electrode, cathode, and anode.

Faraday's electrical inventions would endure a lengthy delay before their practical application. His work in electrolysis was eventually deployed by the fourth generation in our lineage: the generation of two electrochemical entrepreneurs, Charles Hall and Herbert Dow. In the 1880s Charles M. Hall (1863–1914) developed a new electrolysis-based method for producing aluminum. Hall's commercial enterprise, the Pittsburgh Reduction Company, later renamed Alcoa, involved the large scale-up of electrolytic processes. Hall's operations soon moved to Niagara Falls to satisfy the operation's need for hydroelectric power. Chemistry and electricity were now connected on both the research and industrial fronts. Reflecting this connection, in 1902 the Electrochemical Society was established in what was by then the industrial and manufacturing city of Philadelphia.

Another example of the chemistry and electricity arena shifting from the laboratory to the industrial plant is Even's Mill. Herbert Dow (1866–1930), fresh out of the Case Institute of Technology, was at the leading edge of electrochemistry. He set up his industrial operation in a former flour mill, Even's Mill, where he successfully electrolyzed brine on a major scale to produce bromine—the much-in-demand essential ingredient in bromides, or tranquilizers. For their manufacture of this popular medicine, a Philadelphia firm that is today part of Merck placed Dow's first order for bromine. With this singular bromine order, the Dow Chemical Company was successfully launched, demonstrating yet another combination of chemistry and electricity.

It is at this point that our story ratchets up to another level of complexity, as the word *electronics* is added to the mix. Developed across the first two decades of the twentieth century, it was the vacuum tube that would launch the age of electronics and guarantee the future of radio. In the mid-1930s Arnold O. Beckman (1900–2004), a young chemistry professor at Caltech, made a revolutionary combination of chemistry and electronics when he used the vacuum tube to create an effective pH meter.

Beckman's instrument used vacuum tube electronics to produce a direct measurement of a fundamental chemical property: pH. This revolutionary tool used electrical properties to transform the pace and character of chemical research itself and thereby opened the way for the development of a host of new instruments that employed electronics to yield major clues to the composition of complex chemicals. Electronics was crucial to the radical change in the power and pace of chemical research at mid-century.

Vacuum tube electronics enabled another more generally transformative development at mid-century: the creation of electronic digital computers. In these early years, however, these vacuum tube machines held more promise than practicality. With alarming regularity, one or another of the thousands of vacuum tubes required for a computer failed. The most daunting challenge for the machines' operators was how many minutes they would function before failed tubes closed the computer down.

At that very moment the answer to these computer operators' needs came from a new combination of chemistry and electricity. The whole world of electronics was about to take on a new shape. In 1947, through the work of William Shockley (1910–1989) and others at Bell Labs—less than 100 miles from Philadelphia—the first transistor was created, and semiconductor electronics was born. The essence of the discovery was that, by chemical and physical means, the class of materials called "semiconductors" could be precisely molded into devices with exacting electrical behaviors. The transistor fulfilled the function of the vacuum tube, but better. It was a robust solid with dramatically reduced size and increased reliability. In the last 1940s and early 1950s, electronics was centered on the East Coast, with firms like Philco, RCA, and IBM. Philadelphia was one natural locus of activity—whether as the home of the Solid State Circuitry conferences or as a center for hiring promising young engineers (for example, Robert Noyce, who went to Philco in 1953). However, this eastern and Philadelphia-linked dominance was not to last.

This rapid survey of the engagement of chemistry with electricity brings us to a fateful telephone call made just fifty years ago. That call would tie together the fates of Arnold Beckman and William Shockley, ignite the silicon electronics revolution, change the lives of the individuals who would deliver on the promise of this revolution, and lead to the creation of Silicon Valley. In 1955 Shockley, who had been an undergraduate student of Beckman's, called his professor, trading on their Caltech connection and Beckman's entrepreneurial reputation. Shockley was looking to leave Bell Labs to establish a company to produce a new wave of semiconductor electronics built from silicon. Beckman and Shockley, who had each made significant contributions to the intersection of chemistry with electronics, established the Shockley Semiconductor Laboratory as a wholly owned subsidiary of Beckman Instruments. Beckman Instruments was in Pasadena, California, but Shockley's mother lived—and hence Shockley Semiconductor Laboratory was located—in Palo Alto. Among the individuals who Shockley gathered for his new effort were Gordon Moore (1929–) and Robert Noyce (1927–1990). Moore and Noyce together would fulfill the promise of the silicon electronics revolution at the firms that they created after leaving Shockley's lab: Fairchild Semiconductor and Intel. By their genius and by extraordinary chemical and physical transformations of the major ingredient, silicon, the microprocessor was born—a significant development for society, culture, and the global economy, which is as profound as it is ongoing.