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Editor

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Into the Nano Era

Moore's Law
Beyond Planar Silicon CMOS

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Into The Nano Era

Moore's Law Beyond Planar Silicon CMOS

With 136 Figures

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This snapshot of the IC industry and several opportunities for enhanced growth in the coming nanotechnology era is dedicated, in memoriam, to Robert Cahn and Fred Seitz, who passed away during the preparation of this book.

Robert Cahn (1924–2007), FRS, University of Cambridge,

and

Fred Seitz (1912–2008), Rockefeller University, President, Emeritus
and
National Academy of Sciences, Past President

Foreword
Silicon and Electronics

The readership of this monograph, *Into The Nano Era – Moore's Law Beyond Planar Silicon CMOS* may be surprised to find that there was a time when silicon materials did not reign supreme. While silicon was utilized both before and during World War I for coded wireless detectors, it was quickly replaced by Vacuum Tube Electronics in the late 1910s and 1920s. The ham radio proponents often preferred to use galena (PbS) in the 1920s, a naturally occurring mineral which was much less expensive than polycrystalline silicon. In the late 1930s and with the advent of World War II, however, silicon became the preferred material for radar detectors. Silicon has continued to be the dominant (and pre-eminent) material during the rest of the twentieth century (although germanium and silicon transistors were commercialized during the 1950s). During the last several decades, we have come from the electronics revolution initiated by the transistor in the late 1940s to the microelectronics revolution, exemplified by the integrated circuit (IC) that was invented in the late 1950s, to today where we are on the verge of the nano-technology Revolution. Of course, many other materials are utilized in today's most advanced ICs and surely this will be the case in the nano-technology of the future; yet, the base still appears to include silicon.

Howard Huff and his authors have developed this monograph to guide us into the nano-technology era by focusing on some current aspects of silicon materials relevant to the fabrication of ICs and several potential opportunities in the nano era. The importance of defects and their control, both in the as-grown silicon and during the chip-making process, is emphasized. Indeed, the admonition to make certain that the quality of the silicon used in chips should be examined carefully before rather than after making the chips repeats one of the basic principles that we discovered during World War II. That is, we found by using metallurgical-grade (polycrystalline) silicon in the 1940s that the erratic behavior and irreproducibility of the electronic characteristics of detectors was dependant on the prior history of the silicon material utilized. This monograph not only stirs up old memories of the earlier days but brings me to further appreciate the fabrication of today's opto-electronic devices.

And such also appears to be the case with the "bottom-up" fabrication technology in the nano era. Indeed, it appears that the drive to miniaturization is finally approaching the stage where quantum effects will become of the essence, which is quite an achievement when I recall the ham radio years of the 1920s and the earliest silicon materials utilized for radar in the late 1930s and early 1940s. I wish Howard Huff and the personnel involved in the creation of this monograph and its readership well in the exciting and never-ending journey towards the next revolution in information and communications technology – the nano era.

New York, March 2008 *Fred Seitz* (deceased March 2008)

Foreword
Silicon and the III–V's: Semiconductor Electronics (Electron, Hole, and Photon) Forever

Without silicon and the III–V semiconductors, today's world of electronics does not exist, would not exist, likely could not exist. There is no substitute for the semiconductor, Si ranking at the top. I learned about transistors and semiconductors from John Bardeen, and then about diffused Si devices, in their inception, with John Moll (and Carl Frosch and the oxide) before learning further from work, colleagues, meetings, and journal articles. Very early, for example, it was a trick of junction assembly of my Si tunnel diodes that revealed phonon-assisted tunneling so strikingly (1959), the first unambiguous experiment showing inelastic tunneling, which made it possible for R.H. Hall and me to introduce into solid-state science and technology (via Si!) the now-universal tunneling spectroscopy. Why deviate from Si, why go off exploring the III–V's, when Si proved to be so rich and wondrous – with Bell Labs' oxide and diffused device technology at its pinnacle; indeed, the very technology that, moving west, spawned the "chip" and Silicon Valley? And what about Si, and its further role? Can we now be so bold (so rude) and commit the sin of even asking the question?

At the 1962 Institute of Radio Engineers (I.R.E., now the I.E.E.E.) Solid State Device Research Conference, Art D'Asaro and I engaged in a friendly argument with Bob Noyce in which we defended the case for the III–V's (light emitters) while Bob argued for a still greater future for Si. Bob knew that Art and I, at Bell Labs, knew about Si from the beginning. Why leave it? We, and Noyce, were both right and both wrong! *The two, Si and the III–V's, are complementary.* We need both. We need the electron, hole, and photon, the three so unique in performance and tied together so incestuously across the energy gap. Recall: no energy gap, no semiconductor, no electron *and hole*, no transistor, no light emitter, no solar cell! What else is like this, and technologically so tractable? Nothing approaches the uniqueness of the semiconductor in what it does and in how it allows us to impose, to render amazing tiny sub-microscopic connected active-device geometries in a crystalline substance, in a nano-ordered substance, and as a consequence realize unbelievable electronic functions – the “chip.”

We can now properly ask: When we were shown in John Moll’s group (Bell Labs, 1954–1955) a bag full of DuPont Si needles – nano-rods, as it were – should we have tried to attack at such an opportune moment nano-assembly? To, say, assemble at once active microscopic circuitry? Or should we have proceeded, as happened, to grow crystals from the needles (i.e., “self-assemble” bulk crystalline Si atom-by-atom) and proceed bit-by-bit to the “chip”? To be sure, should we have proceeded, Oh, so slowly but, Oh, so successfully? Who could have predicted, in the beginning, all that would be needed to make today’s Si “chip”? And now, in contrast, where and what is the science and technology of direct nano-assembly? Is it, say, an ultra-tiny complex system that must take on great variety and form and not be just the bland simple atom-stacking of crystal growth? Is this (a complex system) even possible without invoking some form of sorcery, i.e., without facing the abyss of total guessing or outright chicanery? Does it make sense and in what substance? Do we wish to abandon Si? If so, why?

We not only build in Si, it teaches us. For example, it is the Si p–n–p–n switch, in its successful form as the thyristor, that teaches us why a CMOS element in a “chip” breaks down or why a III–V transistor laser switches and exhibits negative resistance. As a matter of fact, it was the p–n–p–n switch that took Si to “Silicon Valley.” It is Si that we have most studied and understand best, and that informs us further in how to realize a still smaller and more sophisticated “chip.” If there is anything past the integrated circuit, the “chip,” it is Si that guides us towards it.

From the standpoint of the III–V semiconductor, heterostructures and direct energy gaps, and quantum wells, we see silicon’s strengths and weaknesses. We see, in comparison with III–V’s, better and worse choices, what can be done profitably and what can not. Silicon, from 1-ton single crystal ingots to the tiniest integrated circuits, is so valuable and such a perfect guide to what is possible in the construction of ultra-small devices, that we must continue to study it. We cannot afford not to, and thus owe a considerable debt to our colleagues Howard Huff and his authors for exposing us to more Si science and technology as we enter the nanotechnology era.

The most questionable topic is that of device self-assembly. We know it works for crystal growth, even in the case of a 1-ton Si crystal, but does it work for the most intricate and tiniest integrated circuits? Note that carbon self-assembles into diamond, but we polish and pattern to develop the mirror facets that make diamond an attractive and expensive jewel. When Si self-assembles, it is too simple. We pattern and process it, at increasingly tiny size, into a more complex and useful form, into an integrated circuit, a “chip.” Now how small can it be, or do we look for other ways (heterojunctions, quantum wells, etc.) to obtain higher performance? Concerning "self-assembly," where and what is the science to make it real and not merely a wish or just a name?

I consider Si and its study, with the aid and added perspective of the III–V semiconductor (and quantum wells), as holding the answer to whether "self-assembly" makes sense. We all get old studying the abundantly rich and fertile semiconductor, but the semiconductor itself, because of the gift of the electron, hole, and photon, and their amazingly connected performance, does not weaken or age. It is not going away. We have no choice but to study Si and the III–V family of materials. Nothing else has worked so well in electronics or promises so much more. There is reason for the semiconductor to prevail, and for us to welcome this new book of Howard Huff and his authors.

Urbana, April 2008 *Nick Holonyak, Jr.*

Preface

The revolutionary impact of the discovery of transistor action by John Bardeen and Walter Brattain of Bell Labs in December 1947 was not anticipated. Similarly, the importance of William Shockley's invention at Bell Labs in January 1948 of the junction transistor (which was not experimentally demonstrated until 1950, although proof-of-concept using a non-colinear configuration was shown in 1949) was not recognized immediately. The transistor's potential was only recognized after it became evident during the 1950s that the transistor – with its much lower power dissipation – could be used to do significantly more than simply mimic vacuum tube electronics in solid-state. It was the invention of the Integrated Circuit (IC) by Jack Kilby of Texas Instruments in 1958 (germanium in the mesa configuration) and, independently, by Bob Noyce of Fairchild in 1959 (silicon in the planar configuration, built upon Jean Hoerni's research at Fairchild in late 1957), that initiated the microelectronics revolution. Even then, however, the implications were barely perceived.

The bipolar IC entered into high-volume production in the mid-to-late 1960s, followed by the MOSFET IC in the early 1970s. Patrick Haggerty's vision at Texas Instruments in the early 1960s of the pervasiveness of the silicon microelectronics revolution, based on the concept of the "learning curve" (i.e., the concomitant reduction in the cost of fabrication with the increased volume of production) and market elasticity, was one of immeasurable significance to the fledging IC industry. Concurrently, Gordon Moore at Fairchild Semiconductor in 1965 made a remarkably prescient assessment of memory component growth, based initially on bipolar and then on MOS memory density trends: A semi-log graph of the number of memory bits in an IC versus the date of initial production was a straight line, representing almost a doubling each year. Moore's observation (updated at Intel in 1975 to about 18 months per doubling and subsequently re-affirmed in 1995) showed that a viable market was indeed practical, and gave impetus to the industry. His analysis became enshrined as Moore's law and set the cadence for technology advancement, e.g., as laid out in the *International Technology Roadmap for Semiconductors* (ITRS). These business-oriented considerations, moreover, combined with Bob Dennard's invention of the one-transistor/one-capacitor dynamic random access memory cell (DRAM) at IBM in 1968 and the related transistor scaling methodologies introduced by Dennard and colleagues at IBM in 1972, established the paradigm for the progression of IC fabrication technology (from a minimum feature size of about 10 µm in the early 1970s, to sub-35 nm in the present era) that has facilitated the explosive growth and application of the MOSFET IC (and subsequently the CMOS IC) during the past 35 years.

The myriad of new electronic products and the creation of new market segments was not (and perhaps could not be) foreseen by the researchers involved. Indeed, Robert Lucky noted in *Engineering Tomorrow* (edited by J. Fouke, T.E. Bell, and D. Dooling, IEEE Press, 2000) that "there is no *a priori* way to determine what will tip a market. It's a fundamental instance of chaos in group dynamics. And that makes it fundamentally difficult to predict future societal behaviors in the adoption of technologies." More than luck is involved; nevertheless, the next application is often a surprise.

And here we are, on the brink of the 50th anniversary of the invention of the IC, in the nano-technology era, wherein critical dimensions on an IC chip, such as the physical channel length, is less than 35 nm. Will silicon continue to be the pre-eminent active semiconductor material, and will Moore's law continue unabated, albeit in a broader economic venue? Indeed, are we wiser now in comprehending that fundamental research, per se, inevitably will lead to new material and device configurations as well as new market opportunities, barely (if at all) perceived at the present time? The research agenda is yet our best opportunity to spawn new innovations to sustain industry expansion to the next major set(s) of global applications.

In that regard, this monograph addresses these questions by reflecting upon the scientific and technological breakthroughs that enabled the microelectronics era, providing a firm foundation for ensuing research, and offering a glimpse of what is to come in the nano-technology era. Accordingly, a review and assessment of topics fundamental to silicon materials and MOSFET device structures is presented, to identify potential nano-technology research directions and possible nano-technology applications.

The monograph is divided into three sections, similar to the format of the Spring 2005 issue of *INTERFACE* (published by *The Electrochemical Society*) from which this book has its genesis. The first section reviews aspects of the historical foundations of our industry. The second section proceeds to examine the silicon material and device structures that are the foundation for state-of-the art IC technology. The third section then presents perspectives of future directions for the nano-technology era. Interestingly, the authors do not anticipate that the current silicon materials/IC industry infrastructure will simply dissolve. The global captains of industry, in-point-of-fact, would not allow this. Rather, the initial new applications in the nano-technology era may indeed come about via integration and merging of new materials with (leading edge) IC structures, forging new applications that may be presently envisioned, even as the IC industry drives towards the sub 10 nm physical MOSFET channel length. It is the anticipation of what comes next, however, that will require our most creative perceptions and, most probably, will produce the greatest surprise(s).

Historical Background

Silicon, and more recently, related group-IV material systems such as silicon-germanium, have been utilized (with silicon) for IC fabrication over the past ∼45 years or so. While silicon and group-IV material systems are anticipated to continue to be utilized in future IC products, the group III–V materials may also concurrently be adopted in order to achieve continued improvement in the device active channel characteristics and related IC performance. Robert Cahn presents an historical perspective of silicon and the silicon revolution in an enchanting introduction titled *Silicon: Child and Progenitor of Revolution*. The phenomenal growth of the IC industry is discussed in a decidedly upbeat fashion by Dan Hutcheson in *The Economic Implications of Moore's Law*. Perhaps Gordon Moore described it best when he recently noted that "... you are once again reminded that this is no longer just an industry, but an economic and cultural phenomenon, a crucial force at the heart of the modern world." Moore further noted that "no exponential is forever; but 'forever' can be delayed." Indeed, we will depend on a new generation of research personnel to maintain and, perhaps, extend Moore's law into the nano-technology world and the next group of big applications.

State-of-the-Art

The characterization, annihilation, and selective utilization of defects to achieve superior IC performance, yield, and reliability is a cornerstone of the IC industry. Because many of the phenomena discussed are structure-sensitive, the "process-structure-property" approach is used to describe the characteristics of modern electronic/opto-electronic ICs which utilize III-V compounds in conjunction with silicon (and germanium again). Specifically, the fabrication process determines the material structure, which in turn determines the subsequent material properties and, therefore, the IC characteristics. Jim Chelikowsky notes that "computers built with silicon can be used to solve for the electronic properties of silicon itself." Chelikowsky reviews these computational approaches from first principles in *Using Silicon to Understand Silicon*. Stefan Estreicher continues this first-principles study of point defects in silicon in *Theory of Defects in Si: Past, Present and Challenges*. These theoretical considerations, in combination with microscopic experiments, have led to an understanding of silicon that is incomparable to that of any other material studied in the technological era. The selective utilization of defects, as grown in the silicon crystal as well as process-induced during device/IC fabrication, and their mutual interactions, has achieved superior IC performance. Andrei Istratov, Tonio Buonassisi, and Eicke Weber pursue several aspects of these phenomena and, in particular, indicate the viability of such an approach for the rapidly expanding defect-engineered silicon photovoltaics initiative (with quantities of silicon usage fast approaching that of the IC industry) in *Structural, Elemental, and Chemical Complex*

Defects in Silicon and Their Impact on Silicon Devices. Materials science and engineering will continue to be critical but it appears that the art and science wherein properties of materials may be dictated not as much by what atoms the materials consist of (taking some liberty here) but rather how they are arranged together will be the *sine qua non* of opto-electronic devices and circuits in the nano-era.

The theme of defects and their control may be further extended by realizing that the surface itself may be considered a giant defect, as noted by H.C. Gatos of M.I.T. and others in the 1960s. The characterization and control of the silicon surface is a fundamental requirement for stable device and IC characteristics. Martin Frank and Yves Chabal present our current understanding of surfaces and interfaces as well as their unique position in silicon micro-electronics, in *Surface and Interface Chemistry for Gate Stacks on Silicon*.

This section concludes with two device-focused articles. Patricia Mooney presents a summary of current trends in silicon-based nano-electronics – in particular the enhancement of carrier mobilities – in *Enhanced Carrier Mobility for Improved CMOS Performance*. The use of variously configured, sequential compositions and combinations of strained silicon-germanium (utilizing carbon as appropriate) to produce strain at the silicon channel surface for various MOSFET configurations permits electron and hole mobilities higher than predicted by the universal mobility curves. Further materials opportunities are noted, wherein an NMOS [PMOS] transistor exhibits optimal electron [hole] mobility for the (100) [(110)] silicon wafer orientation (in the ⟨110⟩ direction for both surfaces). Methods of fabricating substrates to enhance both NMOS and PMOS performance are described as a hybrid orientation technology (HOT), and a simplified hybrid orientation technology (SHOT). Finally, Tsu-Jae King Liu and Leland Chang discuss a host of silicon-based advanced transistor structures and associated materials, based on the conventional "top-down" IC fabrication methodology in *Transistor Scaling to the Limit*. They note that these efforts are expected to extend the ITRS to a physical channel length in the single-digits, consistent with IC leakage current, power-supply voltage, and power-delay product specifications.

Future Directions

The final section of this monograph covers several evolving opportunities for future nano-technology. Ted Kamins discusses the alternative "bottom-up" approach for device fabrication in the nano-world in *Beyond CMOS Electronics: Self-Assembled Nanostructures*. Here we see the concept of "self-assembly," introduced by way of an example in the fabrication of in-plane nanowires (5 nm in diameter by several hundred nm in length) for connections between active circuit components to enhance IC performance. Indeed, we are still basically using silicon and its myriad fabrication process technologies in conjunction with the self-assembly concept.

Mircea R. Stan, Garrett S. Rose, and Matthew M. Ziegler then discuss *Hybrid CMOS / Molecular Integrated Circuits*. The authors look to further the pervasiveness of silicon technology by "piggy-backing" the nano-technology world onto the ever-shrinking IC devices on a chip. In these initial nano-technology applications, the authors suggest that the (nano) molecular assembled structure will be electrically connected to the upper surface of a programmable logic array (PLA), based on majority-carrier logic, with appropriate wiring schemas. It is anticipated that a nanotechnology single-electron transistor can be operated in conjunction with a CMOS logic IC at room temperature (an extremely important requirement), thereby enhancing the performance of advanced logic CMOS devices beyond what they could achieve on their own.

Delving further into the nano-world, Andre DeHon notes that at the current stage of the micro/nano-electronics revolution, we no longer have the orders of magnitude difference between the size of the IC and the constituent atoms, which previously allowed the crafting of large collections of atoms into "perfect" devices. Accordingly, Andre notes that circuit designers and architects now need to take some of the responsibility for dealing with truly atomic-scale imperfections and uncertainty in *Sublithographic Architecture: Shifting the Responsibility for Perfection*. Finally, David P. DiVincenzo discusses *Quantum Computing*. Besides the potential realization of fabricating qubits (quantum bits) in Josephson junction circuits and ion traps, the author discusses the role of semiconductor quantum dots. He notes that III–V heterostructures might indeed facilitate the fabrication of a quantum computer. Interestingly, the scientific literature is also discussing the utilization of an isolated silicon double quantum dot as a qubit. The author notes at the end of his article: "It may be hoped that in ten years the details of this chapter will be thoroughly obsolete, and completely new and unanticipated effects will have been seen and controlled in such a way that it makes the path to a quantum computer clear. We will see." Indeed, we shall see more clearly as we enter the nano-technology era to identify the next big technologies that can be wrought from the nano-world for the betterment of humankind.

Finally, we are fortunate to have four additional brief contributions to the monograph rounding out this perspective of *Into The Nano Era: Moore's Law Beyond Planar Silicon CMOS*. Fred Seitz leads off with a brief introductory comment, *Silicon and Electronics*, about the evolution of electronics over the past 75 years. This is followed by Nick Holonyak's reflections on *Silicon and The III–V's: Semiconductor Electronics (Electron, Hole, and Photon) Forever*. We conclude with two afterwords by the Nobel Prize awardees Herb Kroemer and Horst Stormer. Herb Kroemer's contribution is titled *Nano-Whatever: Do We Really Know Where We Are Heading?*, reprinted from Phys. Stat. Sol. (a) **202**, No. 6, 957–964 (2005). Horst Stormer's afterword is titled *Silicon Forever! Really?*, from the 2006 issue of Solid-State Electronics, **50**, No. 4, 516–519 (2006). Clearly, we will all have benefited by these colleagues sharing their perspectives with us as we enter the nano-technology era.

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We appreciate the contributions of Len Feldman and Konstantin Likharev for their participation in the earlier version of this endeavor, published by The Electrochemical Society in the Spring 2005 issue (**14**, No. 1) of *INTERFACE*. We also appreciate Mary Yess, Deputy Executive Director of The Electrochemical Society, for her

fine assistance during the development of the original *INTERFACE* issue. Appreciation and thanks are due to Claus Ascheron, Physics Editorial IV, Executive Editor Physics and Ms. Adelheid Duhm, Associate Editor Physics, of Springer-Verlag for their strong interest and guidance throughout the development and production of this book. Finally, this book is dedicated to Robert Cahn and Fred Seitz, both of whom passed away during the preparation of *Into the Nano Era: Moore's Law Beyond Planar Silicon CMOS*.

Henderson, NV, April 2008 *Howard R. Huff*

Contributors' Acknowledgement

This volume would not have come into existence without the unrelenting efforts of Howard Huff and his dedicated wife Helen. Howard Huff succeeded to describe in the Preface the whole history of the semiconductor revolution of the last 60 years, but he left out one important person: Huff, as he likes to be called, himself.

First, he promoted the field through his own research at Fairchild, later National Semiconductors. Later, his work had even more impact in the field, we can say Huff's contributions were key for the Si IC technology following the (accelerated) Moore's law. This became especially obvious during his years at Sematech where he was instrumental in establishing the ITRS Si roadmap. He went on to make sure that regular, very carefully worked-out updates were created, mainly by consensus of the members of the different task teams. This careful work made the Si roadmap immensely valuable for all planning processes, especially of the equipment supplier industry. Recently, his interest was specifically focused on issues related to the gate stack and the search for new gate dielectrics. In addition, he was responsible for the big Si conferences organized each four years for more than 40 years with the Electrochemical Society, the proceedings of which contain an impressive body of knowledge in the field of Si materials science and technology, and continue to be frequently cited.

Huff kept saying in the last decade of the last millennium that the Si roadmap is only layed out till 2010 as he will be dead afterwards and thus does not care beyond that date. Well, Huff, in this single instant we might prove you wrong, we expect to have you with us beyond 2010, and the ITRS Si roadmap of course stretches by now far beyond 2010.

It has been a special honor for all of us to work closely with Huff in this book project, and we look forward to exciting initiatives in this important field from Huff in the years to come!

Tonio Buonassisi, *Patricia Cahn*, *Yves J. Chaba*, *Leland Chang*,
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[†] Deceased.

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Part I

Historical Background

1

Silicon: Child and Progenitor of Revolution

R.W. Cahn

Antoine Lavoisier, the pioneering French chemist who (together with Joseph Priestley in England) identified oxygen as an element and gave it its name, in 1789 concluded that quartz was probably a compound with an as-yet undiscovered but presumably extremely common element. That was also the year in which the French Revolution broke out. Five years later, the Jacobins accused Lavoisier of offences against the people and cut off his head, thereby nearly cutting off the new chemistry. It was not until 1824 that Jöns Berzelius in Sweden succeeded in confirming Lavoisier's speculation by isolating silicon. Argument at once broke out among the scientific elite as to whether the newly found element was a metal or an insulator. It took more than a century to settle that disagreement decisively: As so often, when all-or-nothing alternatives are fiercely argued, the truth turned out to be neither all nor nothing.

Silicon and oxygen are in fact the most abundant elements in the earth's crust and are also very common in our galaxy. Why in particular is silicon so common? Our modern understanding of nucleosynthesis got under way at about the same time as the invention of the transistor. The great British astronomer Fred Hoyle in 1946 [1] took the first steps in working out how hydrogen first fused to generate helium and how multiple helium nuclei might then fuse to produce carbon, which in turn would fuse with more helium nuclei to progressively generate heavier elements (all of which astronomers simply call 'metals'). An apparently insoluble energy barrier turned up against the combination of beryllium and helium to generate carbon; Hoyle proposed a possible way around this roadblock and in one of the great triumphs of modern astronomy he combined with several American colleagues to prove in detail that this escape route was indeed correct [2]. The synthesis of elements up to silicon and iron proceed in the interior of stars at temperatures exceeding 10^9 K. Further nucleosynthesis, of heavier elements, mostly takes place in supernovas which are even hotter. Silicon is one of the stablest elements against both fusion and fission, which is very appropriate for an element that has proved so crucial for humanity. Silicon

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R.W. Cahn is deceased.

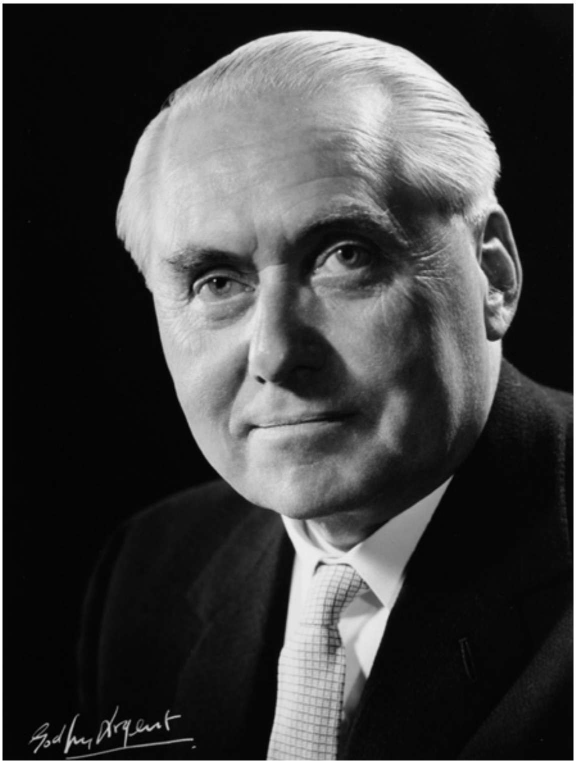
is in fact often used by astronomers as a reference standard when they estimate the cosmic abundances of different elements.

Nucleosynthesis is today sometimes utilised for the improvement of semiconducting devices. The minority silicon isotope ^{30}Si can be transmuted into ^{31}P by bombardment at ambient temperature with thermal neutrons. This was first discovered by Lark-Horowitz in 1951 [3] and later applied to practical devices requiring extremely uniform phosphorus doping: the recent history of this approach, with its benefits and drawbacks, is set out by Wilkes [4].

Towards the end of the nineteenth century, silicon found a growing role as an alloying element for iron. The British metallurgist Robert Hadfield discovered some interesting properties in iron–silicon alloys with a few mass per cent of silicon and very little carbon. Systematic experiments at the end of the century by William Barrett in Dublin, Ireland, culminated in the single-phase iron–silicon alloys that for more than a century have been used for transformer laminations, saving significant money because transformers made with this alloy had very low core losses. The American metallurgist T.D. Yensen (who later introduced the use of vacuum melting for these alloys) estimated as early as 1921 [5] that in the first 15 years of silicon–iron, the use of this alloy family had returned savings in electrical power generation and transmission sufficient to finance the building of the Panama Canal – and this was before the mastery of crystallographic textures further improved the performance of silicon–iron transformer laminations. This early use of silicon thus foreshadowed the extraordinary financial savings and untold applications resulting from the introduction of transistors and integrated circuits, half a century later. A detailed account of the development of silicon-iron was written by J.L. Walter of the GE (Central) Research Laboratory [6].

The electrical uses of silicon began hesitatingly. Crystal rectification, making use of cat's whisker counter-electrodes, developed into early detectors for wireless telegraphy, and coarse-grained silicon of merely "metallurgical-grade purity" (99%) was used until World War I when vacuum tubes began to take over the role of detectors. According to a brilliant historical overview of electronic developments involving silicon [7], Jürgen Rottgardt in Germany in 1938 reported on extensive research into the possible use of cat's whisker crystal rectifying junctions in the microwave region, which was becoming important for the incipient development of radar. Rottgardt concluded that the combination silicon–tungsten was particularly promising as a detector in this wavelength range. This was developed into a practical detector by Herbert Skinner in Britain during World War II, and independently by Russell Ohl and George Southworth at the Bell Telephone Laboratories in America. This approach gradually gained ground against the devotees of vacuum tubes due to its higher operating frequency; each advance in this field was fiercely resisted by the exponents of the preceding orthodoxy. Seitz and Einspruch [7] tell us that in 1941 Skinner wrote a bitter little poem, which included the words: "And so alone / we, fighting every inch of the way, / against those ingrained elephants of inertia / against... prejudice and hardened pride... / we fought (through forests thick with self-satisfaction) / to shorter electromagnetic wavelengths."

A proper understanding of the electrical properties of silicon was slow in coming. The term “semiconductor” appears to have been first used by Alexander Volta in 1782. Humphry Davy in London, in 1840, first established that ordinary metals become poorer conductors as they heat up, while a few years later, Michael Faraday, working in the same laboratory as Davy, discovered a number of compounds which conducted electricity better as they became warmer. Attention soon focused on silver sulphide, Ag_2S, and this was thoroughly studied; this compound is today known to exhibit a semiconductor–metal transition. In the early days it proved impossible to get good reproducibility, and it became the orthodoxy that semiconductors must be impure to function as such and, ipso facto, were not respectable materials because impurities necessarily vary from one sample to another. Until the end of the 1930s, most physicists looked down their noses at semiconductors and kept clear of them; some, like Wolfgang Pauli, expressed themselves in positively violent terms: a semiconductor, declared Pauli, is a “*Schweinerei*”.



Sir Alan Herries Wilson, 1905–1995. Photograph by Godfrey Wilson, collection of the National Portrait Gallery, London, reproduced with permission

The man who changed all this was Alan Herries Wilson, a theoretical physicist in Cambridge, who as a young man spent a sabbatical with Werner Heisenberg in Leipzig and applied the brand-new field of quantum mechanics to issues of electrical conduction, first in metals and then in semiconductors, as reported in two Royal Society papers in 1931 [8, 9]. When he returned to Cambridge, Wilson urged that attention be paid to germanium but, as he expressed it long afterwards in a retrospective essay [10], "the silence was deafening" in response. He was told that devoting attention to semiconductors, those messy entities, was likely to blight his career among physicists. He ignored these dire warnings and in 1939 he brought out his famous book, *Semi-conductors and Metals* [11], which interpreted semiconductor properties, including the much-doubted phenomenon of intrinsic semiconduction, in terms of electronic energy bands. His academic career does indeed seem to have been blighted, because despite his intellectual distinction he was not promoted in Cambridge. At the end of World War II, he abandoned his university functions (a cousin of mine was his last research student) and embarked on a long and notably successful career as an industrialist, culminating in his post of chief executive of a leading pharmaceutical company. He kept clear of electronics.

It was only in the 1940s that n and p-type domains in silicon were observed and their nature identified, by the metallurgists Jack Scaff and Henry Theuerer at the Bell Laboratories, collaborating with Ohl and Southworth. They determined that the sense of rectification in point-contact mode was opposite either side of a p/n junction. Many years later, Scaff published an account of these early researches [12]. The recognition that the way forward for transistor technology lay in the use of single crystals did not come until the early 1950s. Gordon Teal at the Bell Laboratories was the visionary who pushed this recognition through against fierce opposition. Teal, incidentally, was a devoted admirer of Wilson's great book. The process of silicon crystal growth was enhanced by W.C. Dash in 1958/59 in a way that got rid of almost all dislocations and their associated electrical effects. The role of various defects, including dislocations, and more generally the role of materials science in microelectronics "past, present and future" has been surveyed by Mahajan [13, 14].

The other recognition that came in the 1950s was the imperative need for extreme purity, in germanium and in silicon. True, the material for transistors had to be doped to create controlled n and p-type domains, but such doping only worked if it was applied to ultrapure starting material. In those early days, the essential approach was zone-refining, invented at the Bell Laboratories by a chemical engineer, William Pfann: It involved the passage of successive narrow molten zones along an ingot, gradually sweeping impurities to one end. For a decade at least, zone-refining was the inescapable technique for achieving ultrapure, crystalline germanium, at a time when this semiconductor was the material of choice for transistors. However, this technique was not applicable to silicon owing to its reactivity with the walls of the zone-refining chamber material at silicon's melting point of 1414°C. For silicon, thereafter, chemical purification using silicon halides and silane was used. It seems that zone-refining is still used today with germanium intended for radiation detectors. Students of electronics today may not sufficiently appreciate the importance of zone-refining, without which the age of solid-state electronics, including microcircuits and nanocircuits, would have been substantially delayed.

The developments which I have very concisely sketched here are beautifully treated at length in an outstanding book by Riordan and Hoddeson [15]. After the long years during which semiconductors, including silicon, were widely held in contempt, silicon has now become the most studied element in the periodic table, having overtaken iron nearly 40 years ago. The physics, chemistry and processing technology of silicon captivate a ceaseless procession of highly skilled scientists and engineers.

The methods developed for shaping silicon monocrystals on an ultrafine scale, making use of controlled etching, oxidation and vacuum deposition, have recently led to some unexpected applications. The whole field of microelectromechanical systems (MEMS) is based on this technology; materials issues in MEMS have recently been reviewed [16]. MEMS already has some mass applications, including acceleration sensors for automotive airbags and tire monitoring systems, but the newest uses have some way to go before mass application. A recent study describes the microfabrication of a high-pressure bipropellant rocket engine, starting with a stack of single-crystal silicon wafers. The engine, weighing 1.2 g and generating just 1 N of thrust at a thrust power rating of 750 W, might be used "on future generations of spacecraft including microsatellites and very small launch vehicles" and be used for "'servicing existing satellites" [17]. A parallel study describes the design of a silicon micro-turbo-generator [18]. Such a "micro-engine" is intended to be able to produce 50 W of electrical power in a device measuring less than a cubic centimetre while consuming 7–8 g of jet fuel per hour; it would achieve more than ten times the power and energy density of current batteries, at a reasonable cost. As a contribution to this form of design, the fracture strength of silicon on a very fine scale has been systematically examined in relation to factors such as the etching technique used for shaping MEMS [19].

Silicon is used in these futuristic designs not because, in mechanical engineering terms, it is the ideal material (it clearly is not), but because it can be shaped with the extreme precision needed, using techniques perfected in the microelectronics industry.

I have pointed out that silicon is sometimes used as a reference element in assessing the abundances of different elements in the galaxy. This is by no means the only such use of silicon. As long ago as 1956, the International Union of Crystallography resolved to organise a project on the precision measurement of lattice parameters. 16 laboratories worldwide took part, all measuring the same batches of silicon and tungsten powders, and mostly using photographic diffraction methods; the results were published in 1960 [20]. Agreement was only about one part in 10^4, including random and systematic errors. This was disconcertingly poor. Thirty years later [21], techniques had greatly improved, and in fact a silicon powder known unromantically as SRM640B was certified by the National Bureau of Standards (re-named as the National Institute of Science and Technology) to have a lattice parameter determined over 100 times more precisely than the 1960 measurement. In the interim, another completely different approach to measuring the lattice parameter of silicon, this time in the form of a single crystal, was invented by Bonse and Hart [22]. This made use of an X-ray interferometer which came to be known as an “Ångström ruler” [23]. This device is cut from a single highly perfect silicon crystal. X-ray interference produces a series of fringes, the spacing of which is measured by a separate, backlash-free moving crystal and the motion of which is measured by means of an optical (light) interferometer. The X-ray wavelength does not need to be known. The outcome is that the lattice parameter of silicon can be measured in terms of an optical wavelength which is in fact the modern international length standard, and thereby single-crystal silicon became a reliable secondary length standard.

The latest projected use of electronic-grade silicon, the most unexpected of all, is as a tool in one of the last great unsolved problems in metrology: the science of ultimate standards. Of the seven base units of the International System of Units (the SI) – the meter, kilogram, second, ampere, kelvin, mole and candela – only the kilogram is still defined in terms of a material, the standard kilogram, made of platinum-iridium alloy and kept under conditions of extraordinary care, in a vault in Paris. Three of the base units, the ampere, mole and candela, require reference to the kilogram. Metrologists the world over are now engaged in an extremely demanding research program to replace the metal standard with another standard based upon an “invariant of nature”. Two alternative approaches are being examined: the watt balance and the X-ray crystal density (XRCD) method using silicon. The watt balance involves balancing the gravitational pull on a metal mass against an electromagnetic force derived from a coil immersed in a magnetic field: the outcome is to relate the kilogram to Planck’s constant, $\hbar$.

The XRCD method relies on measuring a large-scale mass in terms of the mass of a silicon atom. This method is deeply linked to Avogadro’s constant. Silicon has been chosen because the microelectronics industry has shown how to make a monocrystal of unique perfection and purity. Such a crystal is shaped into a sphere weighing nominally one kilogram, and polished to a sphericity so perfect that if it were expanded to the size of the earth, the highest mountain would be about 7 meters in height. The diameter of the sphere is measured by laser interferometry, and the number of atoms in the sphere is deduced from the lattice parameter, itself measured by means of X-ray interferometry (the Ångström ruler introduced above). The benefit of using a “perfect” sphere is that a single-size measurement (the diameter) suffices to determine the volume of the crystal.

The essentials of both methods, the watt balance and XRCD, and the implications of each for metrology, are set out accessibly in a recent article [24]. These implications are analysed in great depth in two very recent papers [25, 26]; its title is “Redefinition of the kilogram: a decision whose time has come”. However, nobody in the metrology community appears to be willing just yet to express a positive preference between the two approaches – the matter is just too delicate. At present, there is a mysterious mismatch between the results of the two approaches [27].

Both methods have been examined in several countries; the chase is firmly international. Thus, the current silicon sphere has been produced in Australia. Scientists in Germany, USA, Britain, Belgium and Russia are engaged in this enterprise. The next objective is for a Russian team to produce a sufficient amount of silicon enriched to 99.99% in the majority isotope, ^{28}Si, to manufacture a sphere in which the atomic weight is known to a higher precision than for natural silicon. The hope is that such a sphere will reduce the uncertainty of measuring Avogadro's constant (on the basis of the present standard kilogram) to better than one part in 10^7, or alternatively (on the basis of the accepted value of Avogadro's Constant) allow a standard kilogram of silicon to be reproduced with this kind of precision. This whole approach is only possible because of the devoted labours of generations of microelectronics specialists.

My title for this introduction – Silicon: Child and Progenitor of Revolution – indicates that while the identification of silicon in a certain sense derives from a political revolution, its modern study has generated one scientific revolution after another. These revolutions all stem from the world of microelectronics, which itself involves successive revolutions.

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The Economic Implications of Moore’s Law

G.D. Hutcheson

2.1 Introduction

One hundred nanometers is a fundamental technology landmark. It is the demarcation point between microtechnology and nanotechnology. The semiconductor industry crossed it just after the second millennium had finished. In less than 50 years, it had come from transistors made in mils (one-thousandth of an inch or 25.4 microns); to integrated circuits which were popularized as microchips; and then as the third millennium dawned, nanochips. At this writing, nanochips are the largest single sector of nanotechnology. This, in spite of many a nanotechnology expert’s prediction that semiconductors would be dispatched to the dustbin of science – where tubes and core memory lie long dead. Classical nanotechnologists should not feel any disgrace, as pundits making bad predictions about the end of technology progression go back to the 1960s. Indeed, even Gordon Moore wondered as he wrote his classic paper in 1965 if his observation would hold into the 1970s. Semiconductors owe their amazing resilience to Moore’s law. To truly understand their greater impact, one must understand Moore’s law.

Moore’s law is predicated on shrinking the critical features of the planar process: The smaller these features, the more bits that can be packed into a given area. The most critical feature size is the physical gate length; as shrinking it not only makes the transistor smaller, it makes it faster. But we are fast approaching the limits of what can be done by scaling. What changes are needed to keep the silicon miracle going, especially as we approach the nano era? This book examines these changes from a technical standpoint because barriers to Moore’s law have always been solved with new technology. However, these barriers are ultimately expressed economically and have important ramifications far beyond the industry itself. Moore’s law is not only an expression of a powerful engine for economic growth in the industry, but also for the economy as a whole. This chapter reviews Moore’s law and the economic implications that it poses. It shows how the continuation of Moore’s law provides