Guest Editorial
A Practitioner's View: Evolutionary Stages of Disruptive Technologies

***Abstract*—Researchers at Sandia National Laboratories have seen that disruptive technologies when successful evolve into three distinct stages. Each stage is characterized by a distinct market size and level of infrastructure. Each stage elicits specific behavioral responses. Stage I is achieved when the proposed concept is demonstrated. At this point, the technology has not found a market and essentially none of the required infrastructure exists. In Stage 2, the emergent technology establishes a specific application for a limited market, which enables the development and maturation of a limited infrastructure. Stage 3 is achieved when the technology achieves widespread application in the solution set for product developers. Experience suggests that Stage 2 is achieved only when the disruptive technology can provide a unique solution to a problem of substantial importance. However, to expand to the commercial maturity accomplished in Stage 3, the emergent technology must either continue to find important but unresolved problems or alternatively must compete for differential advantage against the defensive innovations of established technologies in the targeted application areas. "True believers" who are committed to the emergent technology sustain Stage 1 and Stage 2 activities. Finally, the authors note the importance of targeting the correct application area to evolve the technology from Stage 2 to Stage 3 behavior. The evolution from Stage 2 to Stage 3 can be considered a coupled system as the emergent technology encounters feedback from the marketplace and competition from established technologies. These factors introduce nonlinearities in the system, making the application of traditional linear technology forecasting techniques problematic for emergent technologies. The authors provide anecdotal evidence in the form of a case study centered on ion implantation, a disruptive technological step in a sustaining technology platform.**

I. INTRODUCTION

NOVEL technologies often are developed prior to establishing unique application arenas that can provide the financial support for their further development and maturation. In some cases, after creating new technologies, innovators either in a national lab or in commercial enterprise rush to identify some product or process challenge for which their invention provides a viable solution. In other cases, a novel technology is the result of targeted development for a limited application. At Sandia National Laboratories, we have observed the evolution of robust and successful disruptive technologies. We have found that the successful disruptive technologies that achieve widespread application typically follow three stages of evolution. Each stage has a different level of infrastructure, a characteristic market position, and elicits distinct behavioral responses. In this paper, we present a practitioner's view of this process. We present the three stages and provide a case study demonstrating its value anecdotally.

A. The Three Stages of Technology Development

Stage 1. Proof of Concept: We consider a technology as having reached the first stage of maturity once the inventor demonstrates the proof of concept. At this point, many times, no commercial market has been identified and the supporting infrastructures of scientific understanding, engineering design, process and product development, manufacturing, reliability, productization, etc., have yet to be developed. The emergent technology is sustained by targeted research and development investment, from government or corporate funding, and occasionally, venture capital.

The emergent technology reaches this first stage of maturity only by overcoming the common behavioral objection: "That idea will never work!" – an objection which is only overcome by successful demonstration of the technology. However, proof of concept does not mean a technology can engage—let alone identify—a market to sustain itself. At this stage, people who are committed and dedicated to the commercial success of the technology which we refer to as "true believers" support the proof and evolution of the emerging technology.

Stage 2. The Emerging Technology Establishes a Limited Application: We have observed that a potential successful disruptive technology clears a major hurdle in commercialization and reaches a second stage of maturity when it has established itself as the only viable solution for at least a limited application area. At this point, a limited market has emerged, along with sufficient supporting infrastructures of scientific understanding, engineering design, process and product development, manufacturing, reliability, productization, etc., to enable profitable manufacturing. The emergent technology may still benefit from targeted investment, either from government funding, corporate R&D, or venture capital,but now revenues from its initial market penetration supplement this investment.

The emergent technology has reached this second stage of maturity only by overcoming the common behavioral objection: "Why use such an unproven approach instead of a conventional one?" These objections are overcome when an important product or process cannot be realized economically—or at all—by any means except the new technology.

The "true believers" continue to play the key role in technology maturation and commercial evolution; however, "converts" are now being made who proselytize the technology, thereby continuing the maturation and development of the emergent technology.

This initial incorporation of the new technology forces (at least) limited use of the new technology and establishes a market

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for the technology. In turn, the initial application market justifies further investment/reinvestment as necessary to provide the revenues and the user base that matures and sustains the technology while developing the infrastructure required to expand the emergent technology into new application areas. The inability of established technologies to resolve the problem in which the emerging technology establishes its toehold is key to the evolution of disruptive technologies.. This was indeed the case for ion implantation, our illustrative case study, as it became the dominant doping technology in semiconductor manufacturing (Myers [20]).

Further, many times the key concept behind emergent technologies has been known for years or even decades. In the graduate classes he taught at Illinois, Bardeen would point out that had Schottky only examined minority carriers, he could have invented the transistor in the 1930s, yet the transistor only emerged from targeted development at Bell Laboratories at the end of the 1940s. Specific to the examples considered here, Shockley filed a patent application for ion implantation in 1954 (Shockley [28]). Yet it was not until the 1970s that ion implantation was widely applied to semiconductor device manufacturing (Sansbury [27]) Similarly, the fundamental idea behind strained-layer semiconductors was described by Frank and Van der Merwe in 1949; yet, the pioneering application of strained-layer heteroepitaxy was not achieved until the mid 1970s by Matthews and Blakeslee.

One reason for this time delay is that emergent technologies trigger defensive innovations by established technologies [33]. However, in a political sense, Machiavelli [19] observed the same phenomenon in the 16th century: “And it ought to be remembered that *there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things*. Because the innovator has enemies consisting of all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new.”

The observation that an emergent technology can reach Stage 2 maturity only when it provides a unique solution to a sufficiently important problem has been expressed by many. We propose that this lesson is so pervasive that it is rarely noted explicitly. For example, Mello, writes: “Look closely at the products emerging from disruptive technologies. … They were breakthroughs because they met the latent requirements of the customer before the customer became aware of the need.” (Mello [19]).

Stage 3. Widespread Application: The third stage of maturity is the most difficult for an emergent technology to achieve. Here, the technology has established itself as the dominant preferred solution for multiple major application areas. At Stage 3, the multiple markets sustain and draw upon a supporting infrastructure of scientific understanding, engineering design, process and product development, manufacturing, reliability, productization, etc. At Stage 3, the once-disruptive technology now is widely taught and widely practiced. Product designers rely on the technology as a preferred tool in their suite of technological solutions.

The integrated circuit is the exemplar of modern disruptive technology; however, the integrated circuit has become so pervasive in modern life that we tend to take its history for granted. In that regard, it is instructive to examine the history of the integrated circuit as described by its early pioneers. In the mid- to late-1950s, visionaries in the semiconductor microfabrication arena foresaw the need for more than a few transistors on a single piece of silicon. They were the true believers that changed the process of semiconductor microfabrication from the “grown junction” manufacturing process technologies to planar technologies developed by Kilby and Noyce [13]. In the late 1950s, this new technology became available as the integrated circuit, the technology base that advanced semiconductor manufacturing into the modern era.

Yet even here, Kilby [14] relates that he saw the need for miniature electronics in applications such as hearing aids, which were marginally profitable at the time. After successfully demonstrating the technology, Kilby reported, “Reactions were mixed.” However, he found a military application of sufficient importance that could not be addressed by discrete transistor technology (in his case, a request for 22 special circuits for the Air Force Minuteman missile) that provided a sufficiently large market that Texas Instruments was able to invest in large-scale production. Once established in large-scale production, integrated circuits developed applications that went so far beyond their initial military application that these silicon chips now pervade all aspects of modern life.

Transitions Between Stages: In examining historical precedents presented below, we found that in most, but not all, cases the initial concept lay dormant for many years before being successfully demonstrated and achieving Stage 1 maturity. It takes time before people who not only have the insight but believe in it strongly enough to advocate the new concept are able to win converts in the larger community—at least in numbers sufficient to attract initial investment. The same phenomenon has been noted in other fields.

“That is, if you say anything which touches a nerve like this you can be absolutely certain that you are saying nothing original. The only possible explanation of saying something which gets excited interest in various different places is, of course, that large numbers of other people have been thinking the same thing and you just happen to be the one character who has put the thought into words. I do impress that on you. There is absolutely nothing original in anything which gets you more or less instantaneous interest.” (Snow [30]).

In that context, Shockley, writing almost two decades after the invention of the transistor, noted a second vivid memory from that time. Shockley recalled that on a train ride from the American Physical Society meeting in New York: “I expounded to a fellow member of the transistor group—and did so, I feel with great clarity, eloquence, and enthusiasm—about the possibility of creating new science about the point-contact transistor by measuring internal contact potentials near an emitter point. At the end of my discourse, I stopped and waited in anticipation for an enthusiastic endorsement. It didn’t come. To my dismay, my colleague's honest evaluation was, in essence, nonsense. I was keenly disappointed. That made the memory vivid. This memory serves two purposes: 1) it confirms a date for the idea initialization and 2) it also shows that they weren't that obvious after all."

The transition from Stage 1 to Stage 2 maturity requires the emergent technology to solve a problem of sufficient importance that it justifies the required investment in a manufacturing base, including essential scientific understanding of the technology sufficient to enable a limited design and production infrastructure. At first consideration, this would seem to be the most difficult stage to achieve. However, if the inventors are able to identify a latent need of the marketplace, their dedication and drive can be combined with a modest source of development funds sufficient to advance the technology beyond mere proof-of-principle demonstrations into limited market penetration.

From a naïve point of view, the transition from Stage 2 to Stage 3 would seem to be fairly straightforward, especially compared to the establishment of an initial market. After all, once at Stage 2 maturity, the emergent technology has developed a limited infrastructure, has established its validity in at least one important application, and has created a limited market to sustain further development.

Yet, history suggests that the transition from Stage 2 to Stage 3 is the most critical in the evolution of disruptive technologies. Recall that Stage 2 behavior was only achieved in a vacuum created when no other technology could address the needs of the emergent technology's initial market. However, for the emergent technology to evolve into wider applicability and greater markets (advance beyond Stage 2 maturity), it must identify or resolve additional important problems that cannot be met by existing technologies. In this regard, selection of the next application after achieving Stage 2 maturity is critical to the rate at which, and sometimes even the eventuality of whether, the emergent technology will be able to advance to Stage 3 maturity (widespread application).

II. THE CASE OF ION IMPLANTATION

The effects of ion bombardment were first studied scientifically in 1851 as a mechanism for the operational degradation of x-ray tubes. Significant advances in the scientific understanding of the interactions of energetic ions with solids occurred during the period of 1930–1945, yet ion bombardment studies were mainly concerned with their impact on high-power vacuum tubes and ion sputtering of solid surfaces (Carter [5]).

The increasing importance of semiconductor (compared to vacuum) electronics led to the Conference on Radiation Effects in Semiconductors, which was held in Gatlinburg, TN, in 1959. However, the on-orbit failure of the AT&T Telstar satellite in 1962 (following the Starfish exoatmospheric nuclear test) provided a major impetus for further investigations of the interaction of radiation with semiconductor devices and circuits. Numerous studies of radiation damage in silicon (Ohl [23]) had already indicated that simple defects could be removed by thermal treatment at relatively modest temperatures (at least by semiconductor processing standards). Shockley generated a remarkably prescient patent later that year. Yet the First International Conference on Ion Implantation was not held until May of 1970 (in Thousand Oaks, CA), to unambiguously demonstrate that ion implantation had become a scientific and technological activity on its own right. After establishing itself as a technique for the controlled doping of metal-oxide-semiconductor field-effect transistors (MOSFET), ion implantation still had to overcome major hurdles before it could successfully displace diffusion technology in the remaining process steps for the fabrication of the majority of transistors and integrated circuits in the late 1970s and early 1980s.

A. *Stage 1. Proof of Concept for Ion Implantation*

In 1954, Shockley filed a patent which elucidated the target application and the entire processing sequence of ion implantation. He suggested that the energy level of the bombarding beam is adjusted so that the projected beam will penetrate into the interior of the semiconducting body. He also suggested a following step be instituted to the semiconductor body to repair the radiation damage done to the surface region penetrated through the process called annealing. Yet, it is not until the 1970s that the following review appears: "As a doping tool, the goal in applying ion implantation is to dope in a controllable way, and to be able to do this selectively; that is, on only certain parts of the wafer. As is well known, the only immediate result of an implant is that it usually creates a damaged region exhibiting generally undesirable properties. The impurity atoms have penetrated the substrate and are at rest inside it, but they have not been activated nor have the damage effects of all the displaced atoms which result from an implant step that has been healed. This is where annealing comes in, and this is where the first great compatibility with other processing techniques arises, for the heat treatments necessary to heal implantation damage and bring about the desired doping behavior are not severe compared to what most wafers are subjected to as a matter of course during thermal oxidation, diffusion, or chemical vapor steps" (Sansbury [27]).

Despite the early understanding in the 1950s, ion implantation could not displace diffusion technology (Grove [11]) for more than two decades. Diffusion technology had been used to create the first bipolar junction transistor (Shockly, [29]). While diffusion technology was well established, ion implantation offered control of doping level (ions are charged, and the number of ions introduced into a wafer can be controlled by integrating the ion current); control of doping depth (through control of incident ion energy); and control of lateral registration (by scanning the ion beam over a patterned mask in contact with the wafer (photoresist, insulator, or patterned interconnect layer,the latter being referred to as a self-aligned gate) [4]. However, these potential advantages were not required by the applications of the time, and ion implantation remained a scientific curiosity until the late 1960s.

B. *Behavioral Responses to Ion Implantation at Stage 1*

The periodic structure of semiconductor crystals is responsible for the electronic properties that in turn enable transistor operation. Properly performed diffusion technology never disrupts the crystalline structure of the host semiconductor crystal. In contrast, ion bombardment results in the generation of interstitial atoms and lattice vacancies due to the transfer of kinetic energy from the incident ion to the lattice atoms during screen nuclear collisions (that is billiard-ball-like collisions).

Although multiple studies had already demonstrated that ion bombardment damage could be removed by thermal treatment to obtain the desired doping behavior from the implanted species (Gibbons [10]), the semiconductor device manufacturing community was still reluctant to incorporate ion implantation into its manufacturing process. Paraphrasing the many radiation-damage experts at the International Conference on Ion Beam Modification of Materials, 1978 [24]: "Any technology that damages a crystal as severely as ion implantation will never find widespread application in electronics." Restated in simpler terms, the community dismissed ion implantation because that idea will never work.

Those initial skeptics blurred the distinction between chemical kinetics (which describes the intermediate stages of a process) with chemical thermodynamics (which describes the ultimate equilibrium configuration of a system). The kinetically controlled implantation process produced defects that were present at densities far above the equilibrium densities of vacancies and interstitials established by bond strengths and the law of mass action. Thus, the metastable defect state immediately following the ion bombardment would recover back to equilibrium defect densities once a kinetic path (in this case, thermal activation sufficient to overcome the kinetic barrier to defect migration and recombination) was provided to the system.

It is not at all obvious that the scientific debate had anything to do with the unwillingness to incorporate ion implantation. The initial ion implanters were research machines that were not immediately adaptable to the rigors of volume production, while in contrast diffusion technology was cheap, enabled high wafer throughput, had a robust supplier infrastructure and was comparatively well understood.

C. Stage 2. Maturity for Ion Implantation

There was no motivation to incorporate ion implantation into the manufacturing process for almost a decade and a half, until a new application was discovered that made the doping control afforded by ion implantation essential. That application was threshold control (control of the transistor turn-on voltage) sufficient to enable a new product: the electronic watch. Doping levels resulting from diffusion technology depended on chemical reactions at the surface of a semiconductor; technology at the time was unable to prepare and sustain the semiconductor surface cleanliness at a uniform level across a wafer and especially from wafer to wafer. This variation in doping level made it impossible to control turn-on voltages of transistors sufficient to operate an entire circuit from an electronic watch battery (Lee and Mayer [16]). However, by integrating the ion current, ion implantation enabled control of the doping level of impurity ions at levels of orders of magnitude more precise than available through growth or diffusion processes (Aubuchon [1]). The ability to produce relatively low cost, yet accurate, time pieces provided a major impetus to the incorporation of ion implantation into semiconductor manufacturing.

Establishing a market for ion-implanted MOSFETs provided more than justification to the implant community. It motivated equipment manufacturers to develop more production-worthy equipment and sparked enhanced interest in the development of the required scientific understanding. A review (Gibbons [9]) proudly announced that: "Currently there are more than twenty laboratories in a total of seven countries doing research and development work on ion implantation in semiconductors. The topics receiving principal attention are 1) range-energy relations for the implanted ions, 2) crystalline sites and energy levels of the implanted ions, 3) structure and electrical effects of implantation-produced damage and its annealing behavior, and 4) device fabrication and characterization. "

D. Behavioral Resistance to Ion Implantation at Stage 2 Maturity

With the advent of threshold voltage adjustment motivated by the creation of a market for low-cost electronic watches, ion implantation achieved Stage 2 maturity. However, ion implantation suffered from a limited infrastructure of scientific understanding, technical support, and (by today's standards) low-performance manufacturing equipment. Paraphrasing a noted industry executive and author of a prime textbook on semiconductor technology statements circa 1960 at a Sandia National Laboratory colloquium. "Nobody will be replacing diffusion furnaces with ion implanters one for one, since diffusion technology is so well established."

What the executive was really stating was the objection: "Why would anyone use such an unproven approach in an application for which diffusion technology is so well established?" The establishment of the electronic watch market through the use of ion implantation overcame this objection. Yet ion implantation still did not replace diffusion technology.

E. Stage 3. Maturity for Ion Implantation

After threshold-voltage adjustment established a market for low-current (and thus low-dose) ion implanters, ion implantation became part of the tool kit for semiconductor device manufacturers. Ion implantation became a key element in enabling the manufacturing of complementary metal-oxide-semiconductor (CMOS) circuits, which have become the industry standard (Dill *et al.* [6]). However, major problems remained before ion implantation could be applied to the majority of applications for impurity introduction in semiconductor device fabrication.

Unlike low-dose implants which created largely isolated defects within an otherwise undisturbed crystalline matrix high-fluence ion bombardment produced extensive damage to the point where under the appropriate conditions, the ion bombardment created so many defects that it totally destroyed the crystalline structure of the bombarded region (made the surface amorphous, or "amorphized" the surface region).

Implantation had already demonstrated not only its feasibility but also its value. However, the implant community was convinced that untapped potential still remained to support additional applications beyond threshold adjustment and self-aligned gate structures in MOSFET fabrication. Seen from this context, the choice of the next application for ion implantation proved critical. From the beginning, a small community felt that ion implantation could provide the same benefits to compound semiconductors (GaAs, InP, InSb, GaP, etc.) that implantation provided for silicon devices. However, the larger implant community focused its attention toward additional penetration of the market for silicon device processing by focusing on using implantation to replace diffusion technology for the creation of heavily doped regions in silicon. This judicious choice proved key to the continued growth and incorporation of ion implantation into semiconductor device fabrication.

Recall that at the time ion implantation was proving useful for MOSFET fabrication; the annealing of heavily damaged—even amorphized—layers in silicon was poorly understood. Furthermore, the ability of the implantation equipment to deliver the high ion beam currents required for creating heavily doped regions without extreme processing delays and simultaneously to achieve the required uniformity across a given wafer stood as obstacles to ion implantation replacing diffusion technology as an industry standard process. These limitations were identified and addressed through targeted research and development. Thus, by the late 1970s, an implantation conference could report: "Ion implantation is now widely used for low-dose applications. …A second generation of applications is emerging. …The *annealing of high doses is better understood* and the technologist is learning how to avoid residual damage. … The original *high-current implanters are now improved in uniformity and throughput*." (Nicholas [21]).

F. Behavioral Responses at Stage 3 for Ion Implantation

The early proponents of a technology are always amazed at the change in response they obtain from the larger community once their dreams for their emergent technology are realized. For example, the same noted industry executive revisited Sandia National Laboratories later in the 1970s. Paraphrasing his new statement yields the following. "A few years ago, I predicted that 'nobody will be replacing diffusion furnaces with ion implanters one for one,' since diffusion technology was well established. Well, I still maintain I was correct. We have been replacing diffusion furnaces with ion implanters three for one."

Similarly, while once a topic for specialist conferences, ion implantation is now a key element in standard texts (Plummer *et al.* [26]). Presently, worldwide sales of ion implanters total $1 billion to $1.2 billion per year.

G. Transition Between the Stages for Ion Implantation

As described above, the concept of ion implantation was well formulated in the 1950s. Yet it took over a decade and a half before ion implantation was able to make serious inroads into semiconductor device fabrication. Ion implantation was only accepted into semiconductor device fabrication after it could be shown to enable a new mass market: electronic watches. This initial commercial application provided the impetus for the "true believers" in ion implantation to advance the once-limited infrastructure of scientific understanding, modeling, process recipes, and manufacturing equipment (ion implanters) into new realms of performance, throughput, and market acceptance that finally resulted in Stage 3 maturity and widespread acceptance. Widespread application of ion implantation as a replacement for diffusion technology was only achieved by targeting technology development toward high-dose applications for silicon processing. While at the time, targeting forward-looking implantation development toward ultimate replacement of diffusion technology seemed obvious (the silicon integrated circuit market in 1970 was orders of magnitude greater than alternative markets for compound semiconductors), the fortuitous choice of higher dose applications in silicon technology was critical from both a scientific and a market sense. The ultimate residual defects present after annealing ion-implanted silicon are dislocations are isolated dislocations (Tan [31]) and yet implantation produces high-quality semiconductor devices.

In contrast, compound semiconductors, semiconductors that consist of an alloy of two or more elements (such as the Group III-Group V semiconductor GaAs), develop higher vapor pressures of the Group V element in ion damaged material (Piciraux [25]) and lead to dissociation rather than recovery of the bombarded material unless the surface is coated with a dielectric layer (Harris and Eisen [12]) or annealed with in an overpressure of the Group V element and /or in combination with rapid thermal processing (Asbeck *et al.* [2] 1985). Further, if amorphized, the surface layers of compound semiconductors will randomly nucleate microcrystals within the damaged region, resulting in poor electrical quality (Eisen [8]). Thus, had the implant community at the time focused its developmental activities on expanding to compound semiconductors rather than expanding into higher dose implantation of silicon, it is not likely that we would see the widespread market for ion implanters and the widespread application of ion implantation to semiconductor device processing that we observe today.

III. CONCLUSION

The disruptive technology of ion implantation evolved through at least two major transitions. Both moved stepwise through the three stages we suggest are characteristic of disruptive technologies. Nonetheless, when an innovator finds the technology has evolved into Stage 2 applications, there is still no guarantee it will successfully pass into Stage 3. In fact, the real measure of a disruptive technology/ discontinuous innovation occurrence is apparent only when Stage 3 is attained. If ion implantation technology had not matured to many widespread applications, we would today not acknowledge it as a disruptive technology. Disruptive technologies are defined by their disruption, not by their invention. Until the existing industry technology paradigm is disrupted, a new technology is just a new technology. For this reason, forecasting the next disruptive technology remains an elusive ambition. It is impossible because of the three necessary stages and the high risk of failure at every stage. Further, small firms are many times first to commercialize the technology even if larger firms are first to the technology providing economic stimulus, jobs, and wealth creation [3], [15].

Furthermore, many have observed that we all know well, individual technologies cannot become commercialized unless other related technologies have developed prior to it introduction (Mansfield [18]). For example, Watt was never able to make his steam engine work until after the machine was invented that could make large diameter cylinders and pistons perfectly round (Usher [32]), Our example of ion implantation developed similarly allowing advances in semiconductor device design. Microsystems and nanosystems face similar problems (Linton and Walsh [33]).

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REFERENCES

[1] K. G. Aubuchon, “The use of implantation to set the threshold voltage of MOS transistors,” in *Proc. Int. Conf. Properties Use of MIS Structures*, Grenoble, France, June 1969.

[2] P. M. Asbeck, D. L. Miller, E. J. Baock, and C. G. Kirkpatrick, *IEEE Electron. Device Lett.*, vol. EDL–4, 1981.

[3] D. B. Birch, *Job Creation in America: How our Smallest Companies put the Most People to Work*. New York: Free Press, 1983, 1987.

[4] R. W. Bower, H. G. Gill, K. G. Aubuchon, and S. A. Thompson, “Insulating gate field effect transistors fabricated using the gate as a source-drain mask,” in *Proc. IEEE Int. Electron Devices Meeting*, Washington, DC, Oct. 1967, 6.3.

[5] G. Carter and J. S. Colligon, *Ion Bombardment of Solids*. New York: American Elsevier, 1968.

[6] J. G. Dill, R. W. Bower, and T. N. Toombs, “Ion-Implanted MOS technology,” in *Ion Implantation*, F. H. Eisen and L. T. Chadderton, Eds. New York: Gordon and Breach, 1971, pp. 349–361.

[7] F. H. Eisen and L. T. Chadderton, Eds., *Ion Implantation*. New York: Gordon and Breach, 1971.

[8] F. H. Eisen, “Laser and electron beam annealing of GaAs,” in *Laser and Electron Beam Processing of Materials*, C. W. White and P. S. Peercy, Eds. New York: Academic, 1980, p. 309.

[9] J. F. Gibbons, “Ion implantation in semiconductors — Part I: Rangedistribution theory and experiments,” *Proc. IEEE*, vol. 56, no. 3, pp. 295–319, Mar. 1968.

[10] ——, “Ion implantation in semiconductors — Part II: Damageproduction and annealing,” *Proc. IEEE*, vol. 60, no. 9, pp. 1062–1096, Sept. 1972.

[11] A. S. Grove, *Physics and Technology of Semiconductor Devices*. New York: Wiley, 1967, ch. 3, pp. 35–90.

[12] J. S. Harris and F. H. Eisen, “The annealing of damage in ion implanted gallium arsenide,” in *Ion Implantation*, F. H. Eisen and L. T. Chadderton, Eds. New York: Gordon and Breach, 1971, p. 439.

[13] J. S. Kilby, “Miniaturized electronic circuits,” U.S. Patent 3 138 743, June 23, 1964.

[14] ——, “Invention of the integrated circuit,” *IEEE Trans. Electron. Devices*, vol. ED–23, pp. 648–654, 1976.

[15] B. A. Kirchhoff, *Entrepreneurship and Dynamic Capitalism*. Greenfield, CT: Praeger, 1994.

[16] D. H. Lee and J. W. Mayer, “Ion implanted semiconductor devices,” *Proc. IEEE 62*, vol. 62 , p. 1241, 1974.

[17] Machiavelli, “Concerning new principalities which are acquired by one’s own arms and ability,” in *The Prince*, 1515, ch. VI.

[18] E. Mansfield, *The Economics of Technological Change*. New York: W.W. Norton, 1968.

[19] S. Mello, “Customer-centric product definition, AMACOM,” *Amer. Mgt. Assoc.*, p. 57, 2002.

[20] D. R. Myers, “Ion implantation of III-V compound semiconductor strained-layer semiconductor systems,” *Compound Semiconductor Strained-Layer Superlattices Crystal Properties Preparation, Trans. Tech.*, vol. 21, pp. 165–198, 1989.

[21] K. H. Nicholas, “Device applications of ion beams,” in *Proc. Trento Conf. Implantation*, vol. 47, 1989, pp. 121–130.

[22] R. N. Noyce, “Semiconductor Device-and-Lead structure,” U.S. Patent 2 981 877, Apr. 25, 1961.

[23] R. S. Ohl, “Properties of ionic bombarded silicon,” *Bell Sys. Tech. J.*, vol. 31, pp. 104–122, 1952.

[24] *Presentation for the Worst Prediction Regarding ion Beams. Banquet 1st Int. Conf. Ion Beam Modification of Materials*, Budapest, Hungary, Sept. 4–8, 1978.

[25] S. T. Picraux, “Vaporization of ion-implanted GaAs,” in *Ion Implantation in Semiconductors and Other Materials*, B. L. Crowder, Ed. New York: Plenum, 1973, p. 641.

[26] J. D. Plummer, M. D. Deal, and P. B. Griffin, *Silicon VLSI Technology*. Englewood Cliffs, NJ: Prentice Hall, 2000, ch. 8.

[27] J. Sansbury, “Applications of ion implantation in semiconductor processing,” *Solid-State Technol.*, pp. 31–37, Nov. 1976.

[28] W. Shockley, “Forming semiconductive devices by ionic bombardment,” U.S. Patent 2 787 564, Apr. 2, 1957.

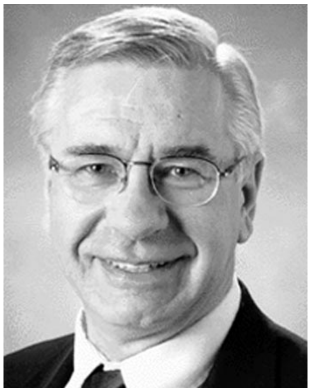
[29] ——, “The path to the conception of the junction transistor,” *IEEE Trans. Electron. Devices*, vol. ED–23, pp. 507–620, 1967.

[30] C. P. Snow, *Recent Thoughts on the two Cultures*. London, U.K.: Birkbeck College, 1961.

[31] T. Y. Tan, “Dislocation nucleation models from point defect condensation in silicon and germanium,” in *Material Research Soc. Symp. Proc.*, vol. 2, New York, 1981, pp. 163–172.

[32] A. Usher, *A History of Mechanical Inventions*. Cambridge, MA: Harvard Univ. Press, 1954.

[33] S. T. Walsh and J. Linton, “Infrastructure for emerging markets based on discontinuous innovations,” *Eng. Mgt. J.*, vol. 12, no. 2, pp. 23–31, 2000.



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