Invited Paper

Evolution and Integration of Optimal IC Design: Performance and Manufacturing Issues

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ABSTRACT

A perspective is presented on how the semiconductor integrated circuit industry has evolved and what we can expect over the next decade or two. However, this "forecast" is given in only the broadest sense, to make it relatively independent on innovations and discoveries that are likely to strongly shape the industry over this time period. Rather, trends are examined, as well as general "tools" that will undoubtedly be important in advancing from our present microelectronics era to our presumable future in nanoelectronics.

Keywords: Microchip, optimization, simulation, CAD, manufacturability, novel devices, nanoelectronics

1. INTRODUCTION

The present article provides a perspective on how the semiconductor integrated circuit industry has evolved and what we can expect over the next decade or two. This "forecast" is intended in only the broadest sense. Of course it is exciting to speculate on the potentially wonderful discoveries and advances that are likely to occur in areas such as nanotechnology, bioengineering, optoelectronics, etc., and how we may well find considerable merging and cross fertilization of these disciplines over the next few decades. However, this article will largely not get into such discussions. There are just too many unknowns, particularly in an area so highly dependent on inventive technological change. Instead, we will focus on likely trends that rise above any specific new technological introduction. Understanding these likely trends should be helpful for anticipating, planning, and adjusting for change in the future. We will then focus on general actions that should be important for the industry during the next five to ten years.

Nearly by any metric that one think of applying, the microelectronics industry is without equal in the history of humankind due to its nearly four decades of essentially exponential, manufacturable product improvement. To support this claim, probably the most publicized success of the industry has been "Moore's law," which observes that roughly every three years or less, the number of devices on a single DRAM chip has increased by a factor of four.[1,2,3] Leading DRAM chips had about 4 K transistors in 1975; by 2000, the number had climbed to about 256 MB. Corresponding to this increase, device dimensions shrunk enormously, falling from about 4 μm in 1975 for the minimum critical dimensions, to about 0.18 μm in 2000. With that shrinkage has come exponentially faster and faster switching speeds. Moreover, and equally as important, the price per transistor has dropped about six orders of magnitude since the sales of single packaged semiconductor transistors, nearly four decades ago. These facts make a strong case for microelectronics providing the leading number one example of technological product growth in history.

Dennard's article in 1974 showed roughly how MOSFET device parameters needed to scale to enable continued shrinking of this core structure.[4] Despite this elegant, but relatively simple recipe, this phenomenal progression has by no means been a "turnkey" operation; huge numbers of barriers have needed to be overcome, as witnessed by the continual yearly increase of semiconductor related patents.[5] Nevertheless, the basic physical ideas have been present to enable continued decreased scaling to occur.[4,6,7]

Yet, the microelectronics industry is, without doubt, at or fairly near a crossroads that will need to be bridged if such progressions are to continue. As has been proclaimed for some time now, physical limitations are well known to exist that will prevent the continued shrinking of "conventional" transistor devices that the microelectronics industry has come to plan for and expect.[8,9] Moreover, incremental improvements that enable us to move closer and closer to these physical limits, become more and more expensive. Most recently,

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surprisingly, there has been some alleviation of such concerns, as the microelectronics industry has actually exceeded "Moore's law" progression trajectory.[10] Nevertheless, although the pace has picked up, few doubt that the inherent physical limits still exist; the recent accelerated pace may simply cause the transition period to come that much sooner, from our present planar MOSFET base to a much different device platform. This article addresses this time period, between now and when the next platform exists.

What will the structure of the next major device "base" look like? The nanoelectronics field[11] is now springing up, with potentially revolutionary changes in switching and memory devices that include novel ideas of truly three-dimensional semiconductor structures, carbon nanotubes, organic molecular approaches, "self-assembly" ideas, optoelectronics, a plethora of possible quantum mechanical based devices such as atomic-scale dots, and all sorts of combinations of these ideas. Without question, each of these directions is worth deeper investigation, as it is too early to know their full potential and deficiencies. At present, a key concern to all of these directions is their manufacturability, something which the microchip industry has been blessed with for some time. Will the new technology base of the future launch a new wave of continued technology improvement, as has occurred during the past several decades? No one knows. All we know is there is considerable potential for new and exciting devices, materials, and assembly of such systems.* Whether the same rate of growth will occur, or more, or less, is purely speculative at this point.

So, what can be predicted with some confidence? Our article consists of the following outline. Section 2 briefly reviews several key aspects why the microelectronic revolution has been so successful, as compared with any other period in technological history. Understanding these points seems helpful for attempting similar advances in our next technological phase. We will assume there will be a new technology revolution to replace the (largely) MOSFET semiconductor platform of the past few decades. This platform certainly seems likely to be rooted in one of the many directions that have been well publicized in the nanoelectronics and advanced microelectronics arenas. However, we will largely concern ourselves here with the issues in Sec. 3, namely, the transition period from our present planar MOSFET based world to this new platform technology. Here it seems likely we can indeed speculate with more certainty, as we appear to have the start of this transition occurring already. We end this article in Sec. 4 with a few concluding remarks.

2. BRIEF EXAMINATION OF RECENT TECHNOLOGICAL REVOLUTIONS

2.1. Microelectronics: Why has it been so successful?

There are a number of reasons why the semiconductor microelectronics industry has been so successful. We will list a few very different, but seemingly important reasons, before settling on three that we particularly want to emphasize.

First, silicon has been the main workhorse. It is very abundant and very inexpensive. Moreover, most of the other material components in microchips are also relatively inexpensive. The cost in fabricating microchips largely lies in the labor of design, manufacturing, and testing, and all the highly expensive equipment costs to enable these tasks.

Second, there has been a near insatiable appetite for the improved products produced by microelectronics. More specifically, as long as the industry has been able to produce faster chips with more memory, there has not been much problem with finding a customer base for purchasing these improvements. Part of the reason lies with the continued complementary development of software programs that run on these chips, as well as the complementary set of hardware systems like PCs, cellphones, smartcards, etc., that gain in performance via these improvements. The software industry has not faltered in making enormous use, and yet still asking for more, in terms of computational/data crunching power from the microchip fabrication industry. This aspect has been enormously helpful for both aspects of this joint industry. Without new software applications (office programs, spreadsheets, educational programs, graphics, games, etc.), most consumers would have little need for the vastly more powerful PCs that exist today.

A third factor that has enabled continued growth, is that semiconductor and thin film technology has proven to be a very rich one in terms of innovation possibilities. Just as the electrical era of the telegraph, telephone,

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*See, for example, the very interesting report in Ref. 11.

electric light, electric motors, generators, etc. (*i.e.*, we are thinking here of the time period of Edison, Bell, Tesla, and so many others) was rich in terms of innovative possibilities, so also has proven to be the case for the present era of microelectronics. In some ways this has been surprising, since for anyone working in the silicon development area, one knows only too well the difficulties of controlling things like "punch through", short channel effects, hot carrier effects, leakage mechanisms, enhanced diffusion effects, etc. However, fortunately what has come out of pushing on these complicated set of problems, has been a rich variety of physical tools and techniques.[12,13,14] A strong reason why the area of microelectronics has progressed so far is that technologists have been forced to study various physical problems they have encountered in great detail, thereby enabling them to gain knowledge to provide the means to further control and manipulate processes to their advantage. Indeed, the present excitement of scientists contemplating the nanoelectronic era originates directly from this attitude, to control systems even down to the individual molecular and atomic levels, thereby greatly widening the possibilities of future activities.

Although these points are clearly important ones for the past success of microelectronics, what we really want to focus in on are three other aspects. The first is "manufacturability." Microchips are an amazing product in that they are readily mass produced. The work that goes into making one chip is not that significantly different from the work that goes into making hundreds of other chips on a silicon wafer, at the same time. Performing an oxidation, ion implantation, diffusion, deposition, or etching step, for one chip on a wafer, is comparable in terms of labor for the same operations on all the chips on a wafer, and even all the chips on tens of wafers at once. Only the exposure step in photolithography largely requires stepping from one chip to another, so this operation does have a significant component that scales with the number of chips on a wafer.

The second key aspect is that microchips have had the enviable position of achieving all the right goals with the *same* development thrust, namely, of shrinking the devices. Miniaturization has enabled: (1) the speed to increase; (2) the logic capabilities and functions of a single integrated circuit (IC) and the storage capacity of a memory module to increase by increasing the number of devices; and (3) the cost per device to scale down. All objectives have been accomplished at the same time and in the same way, by continued miniaturization. This is really very unique when compared with other manufactured products (cars, planes, TVs, radios, clothing, food products, etc.) in history; usually, when performance of a product goes up, cost goes up, or, at the very least, certainly the cost does not scale significantly *down* when performance/quality scales up.

The last key point we will mention we find the most interesting, namely, the tools and products of this industry have helped fuel its success, and in a very significant way. Probably more so than any previous technological revolution, microelectronics has helped spur its own progress by increasing the capabilities and productivity of all its workers and by enabling the development of critically important tools and instrumentation. An obvious example of this point is the personal computer (PC) or workstation. Nearly every engineer and scientist has a dedicated PC (often more than one) they constantly use throughout their daily work. Moreover, microelectronics continually provides improved computers for storing, tracking, and analyzing huge quantities of data to monitor the development and manufacturing of semiconductor based products. Sophisticated simulation programs have been, and continue to be, created and enhanced for designing and testing of the chips at nearly every stage of these processes. In addition, microchip products have provided increasingly sophisticated microprocessors for controlling semiconductor manufacturing equipment such as SEMs, etching and deposition tools, lithography projection tools, ebeam writers, etc. Statistical process control and feedback systems have been advanced enormously due to the capabilities of computers and microprocessors.

It would be hard to think of another manufactured product, as compared with the microchip, that has aided its own development so much. Perhaps the next best candidate might be something like electric motors, robotics, or "machinery" in general, as such developments have undoubtedly aided in creating tools and processes that improve their own manufacturability. But, it seems a much bigger stretch to claim that such products have had the same huge degree of influence on their own development as is the case with microchips.

2.2. Other "recent" technological revolutions

For so many of the reasons we just discussed, clearly the microelectronics industrial period is a unique phase in technological development. However, that does not mean this phenomena is without precedence. Other incredibly important technological revolutions have taken place in history; each have had their "glory" period, where technological growth was very rapid, before eventually slowing down and giving way to some other era. Consequently, perhaps a brief examination of these past periods may help suggest what the future holds for microelectronics, at least in terms of the general pattern of change.[†]

Starting largely in the last several decades of the 1800s, an impressive electromechanical revolution took place, revolving around the use of electricity being converted to other forms of energy such as mechanical (electric motor and all the things that it powers: conveyor belts, electric drills, saws, lathes, fans, vacuum cleaner, subways, ...), light (incandescent light bulb), sound (telegraph, telephone, electric bell, phonograph), heat (electric stove and electric refrigerator), and other variations of all of these, such as motion pictures. Many of these devices aided in the productivity of the workers developing these technologies, by providing electric tools and machinery, as well as lighting, heating, and communication tools.

The revolution in transportation involving the automobile and airplane had direct connections to developments of the gasoline and diesel engines; these events clearly changed the world by making connections between people possible on a far more frequent and convenient basis. In many ways, this industry also helped to fuel its own development, as the development of these vehicles required the transportation of large quantities of materials like metal, fuel, glass, rubber, etc.

Other more recent technological revolutions have encompassed the inventions of radio, television, and plastics. From each came large industries, not only for these specific areas, but also in many connected industries, such as the entertainment and news industry for radio and television, and building materials, toys, clothing, etc., for plastics and synthetics.

Why mention this? Each of these industries is now in a fairly mature state of their production and manufacturability; each of these industries still have a healthy business, although clearly their growth in terms of performance and economics is not on the steep curve that has been characteristic of microelectronics. However, at one time, each of these industries rose fast, and helped fuel the economy of much of the world. Microelectronics may be heading to the end of its fast rising product platform. Unless another platform takes over within five to ten years or so, this fast rising performer will hit a transition period that may resemble the form of what other technology revolutions have incurred.

3. TRANSITION PHASE

3.1. What May Naturally Happen

Our own guess is that there will be at least one device platform, and quite possibly more, that takes the place of the planar MOSFET structure in microelectronics. Nanoelectronics just seems too incredibly rich[11] in terms of technological possibilities for this not to happen. Moreover, there exist a number of possible semiconductor novel device structures, such as FinFET[18,19] and double gate structures,[20] that may provide a basis for new device platforms.

However, there may well be a transition period during which growth (performance improvements in terms of individual devices) will not be on the fast track that it has been on. After all, the factors that have made microelectronics such a fast rising industry are hard to duplicate. In particular, of the factors discussed in Sec. 2.1, probably the hardest one for nanoelectronics will be achieving the manufacturability of the new products, so that they can truly be mass produced. Even for novel microelectronic structures, issues such as a manufacturable lithography process, or ensuring that statistical fluctuation of dopant distribution in such small devices does not significantly hurt process windows, are key manufacturable concerns.

Suppose a transition period does set in. No one talks about it much, but, clearly this is very possible. What will happen? What should happen? There are some obvious factors, and there are some more subtle ones. In the present subsection, we discuss some of the more obvious factors that may well naturally happen; we then turn in Sec. 3.2 to areas that may require more focused effort.

[†] Of related interest, see Fig. 1-2 on p. 15 in Ref. 15, Ref. 16 for a detailed historical perspective on innovation in the United States, and pp. 142-145 in Ref. 17 for a quick, but very nice summary, of periods of innovative revolutions throughout human history.

The first obvious (or perhaps "naturally occurring" is the proper phrase) result of a transition period has to do with yields. Despite our statement that microelectronics may well be a shining example of technological manufacturing growth in history, nevertheless, this does not mean it is mature in terms of its manufacturing practices. Indeed, in many ways, microelectronics is very immature, as compared with other manufacturing sectors in industry. Without doubt, the semiconductor industry employs leading edge metrology, equipment, tooling, etc., in its manufacturing fabrication facilities. However, yields are horrible, as compared with nearly any other area of manufacturing. Manufacturing sectors in machining, plastics, automobiles, etc., would be shocked to learn the low tolerated yields in the semiconductor industry. Of course, there is indeed a very good reason for this, as the product cycle is so short. Six months on one product, then moving to the next improved DRAM or logic product, is very typical. Products often start out with yields of 40%, then climb to perhaps 80% with continued learning. However, rarely do products have a chance to climb much higher before a product change starts the yield learning curve all over again. The justification, of course, is that moving on to the next product makes more economical sense than staying with the old, as prices typically drop extremely fast on products.

Hence, the following natural outcome should occur if we eventually run into a transition period between device platforms and are not able to adhere to "Moore's law." We can expect to see more focus on yield improvements, rather than such rapid switching to the next product design.

A related second observation, has to do with design methodology of microchips. As noted on p. 342 in Ref. 13, "... the combination of exponential design complexity in sheer numbers of transistors and wires, along with the explosion in the number of design concerns," has lead "... to 'superexponential' growth in the complexity of the design task. To meet these new silicon technology contexts, the design methodology must change dramatically and its tools must be developed in anticipation of these changes." The basic design flow for microchips "... has certainly evolved over the years as new tools have been added to the design methodology, but the major elements of the flow have remained unchanged since the late 1980s".[‡] Consequently, as the physical device basis for microchips reaches the transition period where growth slows from its present fast pace, we may well see opportunities for new design methodologies to be applied to existing hardware that will create startling improvements in chip performance. Thus, the situation for design is rather analogous to that for manufacturing: the slowing down in device improvements should enable manufacturing and design techniques to improve to establish higher yields as well as improved designs, by being able to focus longer on longer lasting products.

Our third observation has to do with the closely associated software products and computer architectures that make direct use of semiconductor product improvements. If semiconductor device performance had not progressed as fast as it has, the software industry would have needed to push harder to take advantage of present computer hardware capabilities. This will undoubtedly happen if the present device performance progression slows down. More emphasis may be placed on yet more efficient algorithms, as well as on improved computer architectures and software that work more seamlessly together. Indeed, at the very least, there is still plenty of potential for further improvements in parallelized computer architectures and associated operating systems. Although such designs are used in workstations in industry and academia, they are still not as widely used as they could be, nor have they really entered the PC market to any real extent. Such designs can be implemented with current semiconductor technology capabilities.

Fourth, the application specific integrated circuit (ASIC) industry, although progressing nicely, is still in its infancy in terms of the wide range of specialized applications that could be tackled, as well as in the use of the most advanced technologies. Leading edge semiconductor devices are still largely reserved for use in the higher volume individual memory and microprocessor products. This will undoubtedly change if microprocessor and memory technology progression slows; the ASIC device hardware should then have a period of catching up to the advanced logic and memory technologies, and technologists will find it attractive to push even harder on more specialized ASIC applications.

Fifth, semiconductor devices have exponentially improved so fast there likely exists many applications still not thought of yet, even using existing semiconductor technology. For example, personal digital assistants

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[‡] See p. 344 in Ref. 13.

(PDA), cellphones, GPA related tools, smartcards, and digital cameras have created a wave of new technological innovation, even though these devices are not encroaching on the Moore's law limit; there still appears to be enormous room for further potential growth in these areas alone. If we reach a period where device performance improvements slow down, then perhaps emphasis will be put on new applications of existing semiconductor device technology.

Our main point here has been to give a few examples that show if and when microchip performance progression slows, the pace has been so fast for so long, there undoubtedly exists plenty of room for progress to be made in closely related areas. Semiconductor device yields, chip design methods, more efficient algorithms and flexible software, computer architecture improvements, ASICs, and alternative microelectronic products using present technologies, should all continue to improve during a possible transition period. Undoubtedly there are many other areas as well, such as needed improvements in verification and testing at nearly every stage of microchip development.[13]

3.2. What May Need Pushing On - System Integration of Manufacturability

3.2.1. Brief overview

The previous subsection discussed likely areas that technologists will naturally focus on, if a period is reached where gains in microchip performance slows. We now turn to our main concern: What areas will the microelectronics industry need to consciously focus on to make solid progress during this transition period? Yes, of course work needs to continue on obtaining, hopefully, the follow-on device platform(s) to the planar MOSFET structure. Nevertheless, we can and should do more than this alone.

We think there are two key areas. Both of them are tightly related to the system integration of manufacturability of microchips. The first has to do with a needed merging of normally rather disconnected areas in microelectronics. The second has to do with a needed focus on the optimization of the overall process. We feel both of these areas can be aided by utilizing an inherent strength of microelectronics, namely, an increased use of computer based resources. Reference 21 touched on both of these issues by examining a specific example involving the optimization of the design and manufacturability of an SRAM structure, by folding in lithography, etching, and general cell design issues.

3.2.2. Needed: Improved coupling of sectors of microelectronics

Regarding the first of the two issues we will discuss here, the following areas in microelectronics can be much more tightly coupled: semiconductor process and device development, microchip CAD design, testing, lithography and mask making, and chip manufacturing. Often the extent of the relationship consists of one group passing off their "finished" result to the next group, with negotiations on what makes suitable "waivers" to enable commitments to be met in reasonable times. Although such relationships can certainly be justified for fast product turnovers, this is not the optimal means for obtaining the best product performance with the highest yield.

Why? Consider a typical interaction between designers, lithographers and mask makers, and semiconductor manufacturers. Designers generally want the smallest achievable structures. They create the chip design given the "ground rules" for what the mask makers can fabricate, with the smallest dimensions possible within the process tolerances needed for manufacturing. Consequently, negotiations about "design rules"[§] are often the extent of the interaction, with subsequent meetings on waivers that one group or the other either wants to retract from or push on harder.

Much more can be accomplished than simply passing a printed set of negotiated rules from one organization to another. The goals of each group are becoming far too widely intertwined to make this previous model of negotiation an optimal one. Designers may want smaller sizes, but, the limits of photolithography and processing exist; manufacturers may want larger sizes and less severe overlay criteria to enable wider process windows and increased yield, but, of course this hurts device and circuit performance.

[§] A reasonably good definition of the typical "design rules" might be: "The set of minimum allowable dimensions required to limit interactions between integrated circuit design shapes are the design rules." See p. 836 in Ref. 22. Further specifications would usually involve single-level and overlay design rules.

Negotiations between groups are generally slow and imprecise. "Requests for waivers are inevitably over design situations that have not yet been built. Without specific experiments run, one's ability is typically poor to gauge accurately whether a waiver is reasonable or not. Consequently, the decisions on most waivers have been, and continue to be, erring on the side of conservatism in design, simply because of this difficulty in being able to make a more precise call on the matter. Clearly, a strong need exists to improve this situation."[21]

Moreover, such simple transfers of information from one group to another does not truly embrace the full information and potential for aggressive design for performance, as well as aggressive design for enhanced yields. Serif structures on CAD designs,[23,24] as well as assist features and yet more complicated patterns of phase-shift mask (PSM) features[25,26] can enormously help the printability of a structure.[14] Yet, to take full advantage of these leverages, they need to be folded into the optimal design of the original circuit and device architecture. Issues regarding proximity of structures to one another, and the specific sizes and shapes of nearby features, are now well understood to play an important role in printability. These features clearly impose constraints on what the device/circuit designer might work with; yet, if used properly, these considerations can make or break the ability to achieve the desired printable critical dimensions (CDs), for a given set of microlithographic tools.

At the manufacturing level, yield is generally the most examined metric of success. Yield can be significantly influenced, not just by improved manufacturing techniques such as strict clean room requirements, but by the microchip design itself. An excellent example of this point has to do with planning microchip layouts to minimize the likelihood of electrical shorts should a contaminant fall on some critical location in a circuit. Such planning can be done by characterizing the probable number of particulates and their size distribution; if design freedom exists in layout constructions, which it often does, then one can fold in this concern. The result can be a significant improvement in yield, due only to this design consideration.[27]

A number of other examples like this exist, where the final product can be greatly improved if information about the manufacturing environment is taken into account in the microchip design. For instance, chemical-mechanical polish (CMP) involves planarizing each wiring level to improve printability of subsequent lithography steps, via alleviating depth of focus issues. This technique can be significantly aided by placing "dummy fill" shapes of various materials that will help control local CMP rates.[28] Thus, an interplay exists here between the physical factors governing CMP, the possibility of inserting dummy shapes of various materials into dielectric insulating regions, and the need to take such issues into account for effects on interconnect capacitance properties.

Such issues are being brought more and more to the forefront, as evidenced by the emphasis during the past decade in microelectronics on the need to "design for manufacturability."[¶] Such issues are not readily resolved, however, as they make the microchip design more dependent on the manufacturing environment; the design becomes less flexible in terms of being able to be readily transferrable from one semiconductor manufacturing facility to another. Still, the benefits are real. To accomplish it effectively, requires more data management considerations and more interaction and direct coupling between manufacturing and design.

Controlling across chip, across wafer, and across lot variations of manufactured semiconductor products, requires high characterization and control of tooling involved in lithography, etching, oxidation, deposition, etc. Design consideration can be very helpful here, as evidenced by the use of dummy shapes, particularly on the outside of wafers, or attention to density of shapes across a chip so as to maintain more global etching balance, can play important roles.

Many other such examples like these are possible. Here are a few that are *not* typically carried out. One could characterize the "footprint" of individual lithography steppers, and restrict the mixing of steppers in subsequent levels to match those that most tightly conform to one another. Such a plan, although doable, clearly restricts the flexibility of a manufacturing line, and requires very high attention and characterization of individual equipment performance, and increased difficulty in managing product flow through the manufacturing line. Nevertheless, better matching of all patterns, and alignment at each process level, could be achieved in this way.

[¶] Conferences exist that emphasize this concept in microelectronics. See, for example, ones sponsored by Semiconductor Equipment and Materials International (www.semi.org), such as the annual IEEE/SEMI Advanced Semiconductor Manufacturing Conference and Workshop (ASMC).

Numerous other examples exist involving yield and reliability issues (*e.g.*: electromigration; probability of crystal defects due to various process steps, and subsequent increased likelihood of leakage mechanisms; radiation hardening; etc.). These examples of lithography printability (serifs, PSM, etc.), across chip variation, CMP dummy fill shapes, and critical area considerations for yield control, all point to an increase in the need to better couple and manage the design through manufacturing process. Normally, yield control is considered to be the exclusive domain of manufacturing, with the solution being to tighten and control process variations. However, at a more global view, yield can also be improved via inclusive process and microchip design that open process windows and reduce sensitivities to key yield and reliability factors.

Fortunately, this growing need to better integrate manufacturing through mask design and through chip design issues, can be aided by playing on one of the key strengths of microelectronics, namely, the availability and infrastructure of powerful computer facilities to maintain data and help manage product flow. Instead of simply passing design rules from one organization to another, much broader rules and guidelines can be enfolded into the algorithms and controls of design tools, along with information that captures the specific character of mask house capabilities and manufacturing equipment characteristics. To a small extent, this is done now; however, much more could be done. A transition period, where product cycles are not changing so rapidly, might enable some focus to be placed here.

3.2.3. Needed: Improved optimization focus

This last point raises the second main issue we want to discuss, namely, a needed focus on what to optimize in the overall product development. Two key issues readily to mind here. First, the obvious one is that, presumably, economics will, and should, be an enormously important factor. Staying on the trajectory of Moore's law, just for the sake of doing so, makes little sense. When the cost versus profits becomes too high to make improvements on the same device platform, then companies will have little incentive to continue to push on this track. Thus, as we near closer to the point where Moore's law reaches its physical limitations on the planar MOSFET platform, the industry will need much clearer targets for improvements versus profits.

Secondly, there are other issues related to optimization. Reference 21 provided a number of specific optimization issues related to the design of an aggressive SRAM design, that combined some of the usual goals of device and circuit layout design with lithography and etching printability issues. The result was a product that had an initial yield in manufacturing that was significantly higher than usual. This article noted specific instances where a merging of cross-disciplines produced a higher level of accuracy of the product goals, and a higher view of what can be achieved. For instance, although the lithography and silicon product world has known for some time that the rectilinear view of CAD designers are inherently inaccurate, to a large extent this information has not infiltrated and become part of microchip circuit design, except in so far as an exchange of simple design rules is concerned. Yet, predictions are now possible for predicting how these patterns print, not just at the photoresist level, but also after etch.[29,21,14] Not making use of this information clearly does not enable the optimum performance structure to be obtained.

As stated in Ref. 21, "At the very least, these simulation methods can be used in 'waiver negotiations' between designers and manufacturing engineers to help better pinpoint whether waivers should be allowed. On a more aggressive scale, design rules may actually be directly based on the simulation of various test cases, or, yet in the most aggressive method, design rules may simply be replaced by the simulations themselves, where the 'coding of the rules' is actually now viewed as being directly encoded within the calibrated phenomenological models that predict how the structures will print."

However, there are far more issues regarding optimization. Once one opens up the entire microelectronic product development for optimization issues, then the previously local goals of smaller designs and faster speeds in the design world, versus the higher yields in the manufacturing world, plus the myriad of other issues involving long term reliability, power dissipation, cost, leakage, etc., become at first blush nearly intractable. Yet, again, we have at our disposal a tool that previous technology revolutions never had. The product we make (microchips and computers) enables the creation of far more powerful tools to take more into account than ever before.

Such optimization problems are not new. As stated in Ref. 13, "Finding the best trade-off among such parameters as design time, cost, power dissipation, and performance is a complex, situation-dependent process, and indeed the notion of trade-off (power versus area versus speed; solution quality versus runtime; etc.) is at the core of design technology."

4. CONCLUDING REMARKS

Very tough problems of continued scaling have existed in microelectronics, as evidenced in such a multitude of physical issues from hot carrier effects,[30] oxide integrity problems,[9] and simply measuring and controlling key parameters like lateral doping profiles.[‖] As difficult as these and other problems have been, the variety of physical phenomena and technical options to address these problems has been equally as rich and deep, as evidenced by the phenomenal yearly number of patents in microelectronics during this period.[15,5] A strong argument can be made that microelectronics has been successful because it pushes on knowing its processes better and better and then using that knowledge to improve them further. Clearly technologists in this field are hopeful to be able to continue this same thrust into the nanoelectronics regime.

The other core reason for this success, as proposed here, is that the product made by microelectronics, namely, the microchip and computer, has enabled its own continued development and growth. The improved product has enabled improved data gathering, analysis, and advanced software design and simulation tools to help the industry keep attacking the technical problems.[**] Perhaps more so than any previous technical revolution, the product of this revolution in microelectronics, may have helped to fuel its own success.

But, we are nearing a stage where it appears that our present planar device platform that has served so well for so long, will not be able to continue being scaled. The possibilities in the future of nanoelectronics[11] seems too rich to expect progress to halt, by any means, but, there may well be a transition period where the progress of shrinking slows, until a new *manufacturable* platform emerges for devices of the future. If so, then as we near this transition period, undoubtedly problems will become increasingly more difficult and more expensive to continue incremental improvements. Section 3 examined the likely trends that may occur, and indicated where continued focus may help to alleviate some of the transition difficulties.

What will happen for the farther future? No one knows. However, the possibilities of nanotubes, self-assembly systems, biological, and optical approaches, merged into the present more conventional semiconductor technology base, should indeed make for very exciting times.

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[‖] See, for example, the brief but nice background discussion on this problem in Ref. 31, as well as the advocated use of atomic probe microscopy in this patent to address this issue.

[**] Many such examples exist here. A suite of examples in semiconductor technology development as far back and prior to 1990, is described in Ref. 32.

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