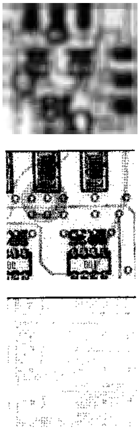

UNDERSTANDING MOORE'S LAW

Four Decades of Innovation

Edited by David C. Brock

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CHAPTER 4

Editor's Note: Gordon Moore's manuscript for his 1965 *Electronics* paper is reproduced here in facsimile, befitting its status as a unique historical document—the first written articulation of Moore's law.

THE FUTURE OF INTEGRATED ELECTRONICS

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If allowed the luxury of a broad definition of integrated electronics to include all the various technologies which are referred to as microelectronics today, as well as any additional ones which result in electronics functions supplied to the user as irreducible units, then the future of integrated electronics is the future of electronics itself. Only a few areas in the realm of electronics do not obviously benefit from the advantages that can be expected from integration.

This paper examines the driving force which will result in integrated functions pervading the electronics art and broaden its scope beyond my imagination. Its purpose, however, is not to anticipate these extended applications, but rather to predict the development of integrated electronics technology for perhaps the next ten years. If one subscribes to the theory of the increasing rate of technical evolution, even such a relatively modest objective is almost certain to result in gross errors.

The origin of integrated electronics probably occurred someplace in the latter part of the last decade with the original objective dictated by the need implied in the term microelectronics. The developing desire to include increasingly complex electronic functions in limited space and with minimum possible weight was the initial motivation. Several approaches to the realization of these objectives evolved, including microassembly techniques for individual components, as well as thin-film structures and semiconductor integrated circuits.

The various technologies have evolved rapidly and convergently. Many people involved in integrated electronics today believe that eventually a combination of the various approaches taking maximum advantage of each for a particular application will be the way of the future. The advocates of semiconductor integrated circuitry are taking advantage of the improved characteristics of thin-film resistors by applying such films directly to an active semiconductor substrate, while those advocating a technology based upon films are developing sophisticated techniques for the attachment of active semiconductor devices to the passive film arrays. Both approaches have worked well and are being used in equipment today.

At present, integrated electronics is an established technique. Most companies in the components business are working with at least one of the several approaches. For new military systems the incorporation of integrated electronics is almost mandatory. In fact, the reliability, size and weight required by some of the systems is achievable only with integration. Such programs as Apollo have demonstrated the reliability of integrated electronics by showing that complete circuit functions are as free from failure as had previously been established for the highest quality individual transistors. Most companies in the commercial computer field have machines employing integrated electronics either in design or in early production. There is little question that these machines will offer advantages in cost and performance over those which can be built using "conventional" electronics. Instruments of various sorts, especially the rapidly increasing array of instruments employing digital techniques, are starting to use integrated electronics, where the advantages of decreased cost, both in manufacture and design, are the principal motivations.

The use of linear integrated circuitry is still restricted primarily to the military, since such integrated functions are still relatively expensive and not available in the considerable variety required if a major fraction of linear electronics is to be integrated. However, first examples of the use of linear integrated circuits are being seen in commercial electronics, particularly where low frequency amplifiers offering the benefits of small size must be employed.

In any case, integrated electronics have demonstrated high reliability. Even at their present low level of production relative to individual components, they offer reduced systems cost. In many instances improved performance is realized. Thus a foundation has been constructed for integrated electronics to continue to pervade all of electronics. Their major impact will be to make electronic techniques more generally available throughout all of society, making available many functions that presently are done inadequately by other techniques or not done at all. The principal advantages which will result in this expansion are lower costs and the greatly simplified design of systems which comes from a readily available supply of low cost functional packages.

Such advantages can be expected to result in the proliferation of electronics. The individual might see the fruits of integrated

electronics in such manifestations as home computers, or at least terminals connected to a central computer, automatic controls for automobiles, or portable communications equipment. The electronic wrist watch lacks only a display to be feasible now. But the principal benefactors of the technology will be the makers of large systems. For example, the telephone communications networks can make extensive use of integrated electronics not only in switching and data processing but by employing integrated digital filters for the separation of channels on multiplex equipment. The computer industry in general will benefit. In addition to being able to make machines similar to those in existence today at lower cost and with faster turn-around, it will be possible to make much more powerful computers perhaps organized in completely new ways. For example, the distribution of memory throughout the electronics will become a practical approach. In addition, the resulting improved reliability allows the construction of larger processing units, although the reliability problems associated with the electro-mechanical input-output equipment might require different solutions.

Not only will the logic portion of computers benefit from the technology of integrated electronics, but other portions as well.

Already, the use of active flip-flop storage for buffer registers is widespread because of the requirements for memory speeds compatible with ever increasing logic rates. Integrated electronics can be expected to expand the range of memory size in which it is advantageous to use flip-flop storage from a speed-cost point of view. The area of random access memory presently supplied by thin films ~~of~~ r magnetic cores can expect active semiconductor memories to begin to compete on a cost basis, first for small, fast memories, possibly more broadly later. Of course, other competing technologies such as ferrite plates, permalloy sheets, and woven wire also show promise of competing with cores. In any case, the peripheral electronics associated with memories will be simplified and reduced in cost by integration.

Next, consider what form the evolution might take and some of the specific accomplishments that might be extrapolated.

The only reasonable candidates presently in existence for the active elements are semiconductor devices. For most applications, where precision of passive elements is not the prime requisite, lowest cost and highest reliability look achievable through the use of semiconductor passive elements as well. Hence, for the major fraction of applications the general technology of semiconductor integrated circuits will continue to predominate. In fact, silicon will likely remain the basic material although others will be of use in specific applications. For example, gallium arsenide will be important in integrated microwave functions. Silicon will predominate at lower frequencies because of the technology which has evolved around it and its oxide. In addition silicon is an abundant and relatively inexpensive starting material.

The cost advantage of integrated structures continues to increase as the technology evolves toward the production of larger and larger circuit functions on a single semiconductor substrate. Figure 1 shows a plot of relative costs per component in an integrated function versus the number of components per integrated circuit for 1962, 1965 and estimated for 1970. Obviously such a curve can only be qualitative, since the actual cost is, of necessity, a strong function of the specific circuit specifications. In this log-log plot at relatively low complexity the cost per component is nearly inversely proportional to the number of components per circuit. This is the direct result of the equivalent piece of semiconductor in the equivalent package containing more components. As complexity increases, at any given point in the evolution of the technology a minimum cost per component is reached, beyond which decreased yields more than compensate for the increased complexity. This minimum in cost per component at the present time is estimated to be in the vicinity of 50 components per circuit. The minimum is moving rapidly toward greater complexity while the entire curve is falling. The bottom curve suggests that in five years the minimum cost per component might be expected in circuits with the order of 1,000 components per circuit, providing such circuit functions can be found that they can be produced in moderate quantites. At such time the manufacturing cost per component can be expected to be at least an order of magnitude lower than it is at present.

Figure 2 shows an extrapolation of the circuit complexity corresponding to the minimum cost per component. The first point on this plot corresponds to the manufacturing of the first planar silicon transistor, which can be considered a starting point for the present semiconductor integrated technology. The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the

near term this rate can be expected to continue, if not to increase. The longer term extrapolation is a bit more nebulous, although there is no obvious reason for stopping the curve before it intersects the top of the graph. This curve was purposely plotted with a rather obscure unit as the ordinate so that the logic of the extrapolation of the historical data might be appreciated without the confusion of the absolute numbers implied. In fact, the top corresponds to about 65,000 components per integrated circuit. One must question the reasonableness of an integrated array of this complexity.

First, even neglecting yield, can so large a circuit be made upon a single wafer?

With the dimensional tolerances already being employed in integrated circuits, it is readily possible to make completely isolated, high performance, transistors on two mil centers. Such a two mil square can also contain several kilohms of resistance or a few diodes. This allows at least 500 components per linear inch or a quarter million per square inch. Thus, 65,000 components need only occupy an area of the order of one-half inch square. On the present silicon wafers usually an inch or more in diameter, there is ample room for such a structure, providing the components can be closely packed and no space wasted for interconnection patterns. This is realistic since a strong trend toward multilayer metallization patterns separated by dielectric films is already evident in order to achieve a level of complexity above the presently available integrated circuits. It is worth noting that this density of components can be achieved by present optical techniques and does not require the more exotic electron beam operations which are being studied for the possibility of making even smaller structures.

Second, is any reasonable extrapolation of present capability compatible with such complexity?

While to those of us in the semiconductor industry it sometimes seems difficult to realize, there is no fundamental reason why the device yields are limited below 100%. Nothing comparable to the thermodynamic equilibrium considerations which often limit yields in chemical reactions exists. Device yields can be raised as high as is economically justified. It is not even necessary that any fundamental information be collected or that present processes be replaced by new processes. It is only necessary that the required engineering effort be committed. At present with respect to individual devices, however, packaging costs generally exceed considerably the cost of the semiconductor structure itself. Thus there is no real incentive to improve the yield of devices on the semiconductor wafer. In the early days of integrated circuitry, the state of sophistication of the processing which had developed for individual components was not sufficient to make the analogous situation true for the integrated structures. Yields on integrated circuits were extremely low. Thus incentive existed to improve the processes. Today ordinary integrated circuits are made with yields comparable with those obtained for individual semiconductor devices. Similar evolution will occur, if necessary, to make larger arrays economical to produce, if such arrays are desirable from other considerations.

Third, is it possible to remove the heat generated by such a function?

By taking a standard, high-speed digital computer and shrinking the volume of the system down to that required for the components themselves, it is easy to show that with the present power dissipations, the resultant mass should glow brightly. In fact, this is not a realistic transformation. In the first place, integrated electronic structures are two-dimensional rather than three-dimensional, leaving a surface available for cooling close to each center of heat generation. Secondly, power is needed primarily to drive the various lines and capacitances associated with the system. As long as a function is confined to a small area on a wafer, the amount of impedance which must be driven is distinctly limited. In fact, it can be shown that shrinking the dimensions on an integrated structure results in the possibility of operating it at higher speed for the same power per unit area. At power densities well below those at which many transistors operate today, one can operate integrated functions at speeds in excesses of those in any systems presently in existence.

Even if such large functions can be made, it is necessary to ask under what circumstances is it reasonable that they be made. In order for it to be reasonable, the total cost of making a particular system function must be minimized. This implies either amortizing the engineering over several identical items, or that flexible techniques be evolved for doing the engineering of large functions so that no disproportionate expense need be borne by a particular array. Perhaps design

automation procedures are possible to translate from logic diagram to the technological realization requiring little special engineering.

It may prove to be economically more reasonable to build large systems out of smaller functions with packaging and interconnection techniques supplying the necessary flexibility. The availability of large functions combined with the possibility of functional design and construction should have a very significant impact on the manufacturer of large systems, allowing him to design and construct a wide variety of equipment rapidly and economically.

As far as the technologies for achieving large functions is concerned, several possibilities exist, any one of which is capable of being developed to the point that these arrays are feasible. It is not clear if one of these will dominate or if a combination will be employed.

One possibility is to continue to require that every component in an array be good in order for the array to be acceptable. Such an approach puts maximum reliance on the processing.

An alternative is to test smaller subunits destined to be connected in the integrated function, selecting those smaller units which are good, then to design a specific interconnection pattern to employ only the good structures in the function intraconnection level. This technique of making a special pattern for each semiconductor wafer, depending upon the pattern of good structures, is being investigated presently in several laboratories. It implies a degree of interconnection flexibility which might also solve the problem of production of small quantitites of special arrays economically, since the flexible interconnection procedures required to avoid bad units should also allow automatic design of various functions.

Other schemes for including redundancy have been suggested. Some involve the use of external logic to avoid bad regions, while others operate on the internal organs of the integrated array itself. In any case such arrays will be achieved. It only remains to see if redundancy will prove useful or not.

While the revolutionary changes integration can be expected to impart upon digital systems cannot be expected throughout linear electronics, a considerable degree of integration will be achieved. The lack of large capacitors and inductors is the greatest fundamental limitation on integrated microelectronics in the linear area. By their very nature, such elements require the storage of energy in a volume. For high Q it is necessary that the volume be large. The incompatibility of large volume and microelectronics is obvious from the terms themselves. Certain resonance phenomena, such as those in piezoelectric crystals, can be expected to have some application for tuning functions, although inductors and capacitors will be with us for some time. The integrated rf amplifier of the future might well consist of integrated stages of gain, giving high performance at minimum cost, interspersed with relatively large tuning elements.

Other linear functions will benefit considerably. The matching and tracking of similar components in integrated structures will allow the design of differential amplifiers of greatly improved performance. The use of thermal feedback effects to temperature stabilize integrated structures to a small fraction of a degree will allow the construction of oscillators with crystal stability.

Even in the microwave area structures included in the definition of integrated electronics will become increasingly important.

The ability to make and assemble components small compared with the wavelengths involved will allow the use of lumped parameter design, at least at the lower frequencies. It is difficult to predict at the present time just how extensive the invasion of the microwave area by integrated electronics will be. The successful realization of such items as phased-array antennas using a multiplicity of integrated microwave power sources could completely revolutionize radar. Such a system is a distinct possibility.

In summary, integrated electronics will allow the advantages of electronics to be applied generally throughout society. While the principal impact will be on digital equipment and will result in much broader use of digital circuit techniques, all of electronics will be strongly effected. There remain many significant problems for the electronics industry to solve in attempting to take advantage of this evolving technology to supply the rapidly increasing electronic requirements of the world.

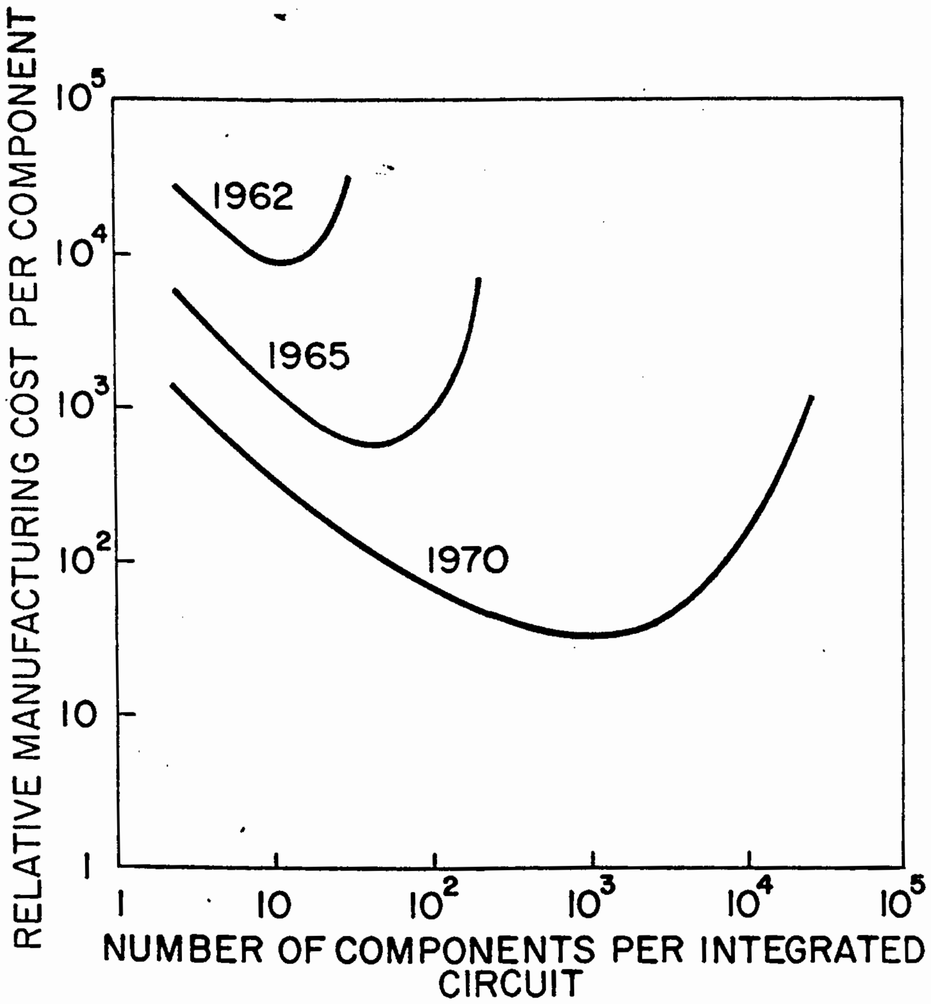

Fig. 1 Estimated relative cost per component vs complexity for a typical integrated function for three different times.

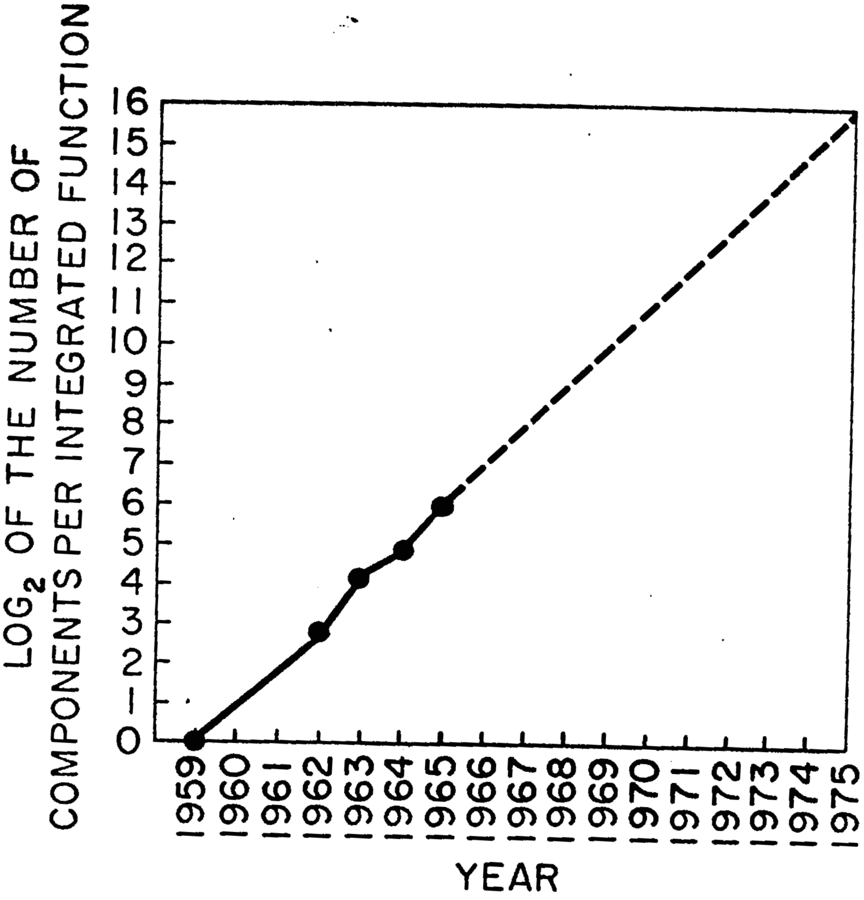

Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.