Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

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The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

But the biggest potential lies in the production of large systems. In telephone communications, integrated circuits in digital filters will separate channels on multiplex equipment. Integrated circuits will also switch telephone circuits and perform data processing.

Computers will be more powerful, and will be organized in completely different ways. For example, memories built of integrated electronics may be distributed throughout the machine instead of being concentrated in a central unit. In addition, the improved reliability made possible by integrated circuits will allow the construction of larger processing units. Machines similar to those in existence today will be built at lower costs and with faster turn-around.

Present and future

By integrated electronics, I mean all the various technologies which are referred to as microelectronics today as well as any additional ones that result in electronics functions supplied to the user as irreducible units. These technologies were first investigated in the late 1950's. The object was to miniaturize electronics equipment to include increasingly complex electronic functions in limited space with minimum weight. Several approaches evolved, including microassembly techniques for individual components, thin-film structures and semiconductor integrated circuits.

Each approach evolved rapidly and converged so that each borrowed techniques from another. Many researchers believe the way of the future to be a combination of the various approaches.

The advocates of semiconductor integrated circuitry are already using the improved characteristics of thin-film resistors by applying such films directly to an active semiconductor substrate. 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.

The author

Dr. Gordon E. Moore is one of the new breed of electronic engineers, schooled in the physical sciences rather than in electronics. He earned a B.S. degree in chemistry from the University of California and a Ph.D. degree in physical chemistry from the California Institute of Technology. He was one of the founders of Fairchild Semiconductor and has been director of the research and development laboratories since 1959.

The establishment

Integrated electronics is established today. Its techniques are almost mandatory for new military systems, since the reliability, size and weight required by some of them is achievable only with integration. Such programs as Apollo, for manned moon flight, have demonstrated the reliability of integrated electronics by showing that complete circuit functions are as free from failure as the best individual transistors.

Most companies in the commercial computer field have machines in design or in early production employing integrated electronics. These machines cost less and perform better than those which use "conventional" electronics.

Instruments of various sorts, especially the rapidly increasing numbers employing digital techniques, are starting to use integration because it cuts costs of both manufacture and design.

The use of linear integrated circuitry is still restricted primarily to the military. Such integrated functions are expensive and not available in the variety required to satisfy a major fraction of linear electronics. But the first applications are beginning to appear in commercial electronics, particularly in equipment which needs low-frequency amplifiers of small size.

Reliability counts

In almost every case, integrated electronics has demonstrated high reliability. Even at the present level of production—low compared to that of discrete components—it offers reduced systems cost, and in many systems improved performance has been realized.

Integrated electronics will make electronic techniques more generally available throughout all of society, performing many functions that presently are done inadequately by other techniques or not done at all. The principal advantages will be lower costs and greatly simplified design—payoffs from a ready supply of low-cost functional packages.

For most applications, semiconductor integrated circuits will predominate. Semiconductor devices are the only reasonable candidates presently in existence for the active elements of integrated circuits. Passive semiconductor elements look attractive too, because of their potential for low cost and high reliability, but they can be used only if precision is not a prime requisite.

Silicon is likely to remain the basic material, although others will be of use in specific applications. For example, gallium arsenide will be important in integrated microwave functions. But silicon will predominate at lower frequencies because of the technology which has already evolved around it and its oxide, and because it is an abundant and relatively inexpensive starting material.

Costs and curves

Reduced cost is one of the big attractions of integrated electronics, and the cost advantage continues to increase as the technology evolves toward the production of larger and larger circuit functions on a single semiconductor substrate. For simple circuits, the cost per component is nearly inversely proportional to the number of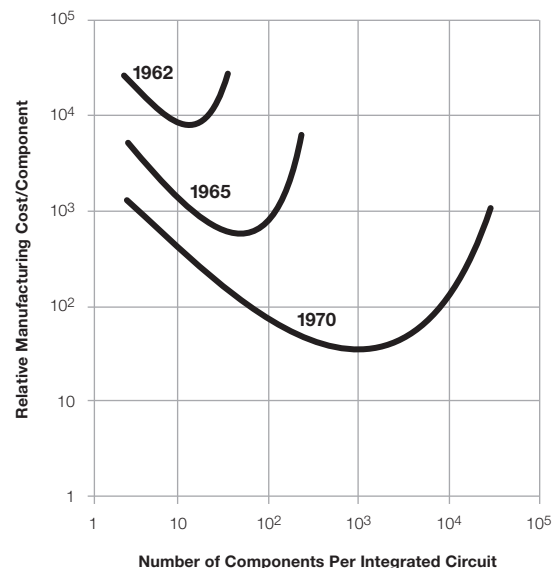 components, the result of the equivalent piece of semiconductor in the equivalent package containing more components. But as components are added, decreased yields more than compensate for the increased complexity, tending to raise the cost per component. Thus there is a minimum cost at any given time in the evolution of the technology. At present, it is reached when 50 components are used per circuit. But the minimum is rising rapidly while the entire cost curve is falling (see graph below). If we look ahead five years, a plot of costs suggests that the minimum cost per component might be expected in circuits with about 1,000 components per circuit (providing such circuit functions can be produced in moderate quantities.) In 1970, the manufacturing cost per component can be expected to be only a tenth of the present cost.

The complexity for minimum component costs has increased at a rate of roughly a factor of two per year (see graph on next page). Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000.

I believe that such a large circuit can be built on a single wafer.

Two-mil squares

With the dimensional tolerances already being employed in integrated circuits, isolated high-performance transistors can be built on centers two thousandths of an inch apart. Such

Chart: Relative Manufacturing Cost/Component (vertical axis, 1 to 10⁵) versus Number of Components Per Integrated Circuit (horizontal axis, 1 to 10⁵), showing curves labeled 1962, 1965, and 1970.

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 occupy only about one-fourth a square inch.

On the silicon wafer currently used, usually an inch or more in diameter, there is ample room for such a structure if the components can be closely packed with no space wasted for interconnection patterns. This is realistic, since efforts to achieve a level of complexity above the presently available integrated circuits are already underway using multilayer metalization patterns separated by dielectric films. Such a density of components can be achieved by present optical techniques and does not require the more exotic techniques, such as electron beam operations, which are being studied to make even smaller structures.

Increasing the yield

There is no fundamental obstacle to achieving device yields of 100%. At present, packaging costs so far exceed the cost of the semiconductor structure itself that there is no incentive to improve yields, but they can be raised as high as

is economically justified. No barrier exists comparable to the thermodynamic equilibrium considerations that often limit yields in chemical reactions; it is not even necessary to do any fundamental research or to replace present processes. Only the engineering effort is needed.

In the early days of integrated circuitry, when yields were extremely low, there was such incentive. Today ordinary integrated circuits are made with yields comparable with those obtained for individual semiconductor devices. The same pattern will make larger arrays economical, if other considerations make such arrays desirable.

Heat problem

Will it be possible to remove the heat generated by tens of thousands of components in a single silicon chip?

If we could shrink the volume of a standard high-speed digital computer to that required for the components themselves, we would expect it to glow brightly with present power dissipation. But it won't happen with integrated circuits. Since integrated electronic structures are two-dimensional, they have a surface available for cooling close to each center of heat generation. In addition, 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 capacitance which must be driven is distinctly limited. In fact, shrinking dimensions on an integrated structure makes it possible to operate the structure at higher speed for the same power per unit area.

Day of reckoning

Clearly, we will be able to build such component-crammed equipment. Next, we ask under what circumstances we should do it. The total cost of making a particular system function must be minimized. To do so, we could amortize the engineering over several identical items, or evolve flexible techniques for the engineering of large functions so that no disproportionate expense need be borne by a particular array. Perhaps newly devised design automation procedures could translate from logic diagram to technological realization without any special engineering.

It may prove to be more economical to build large
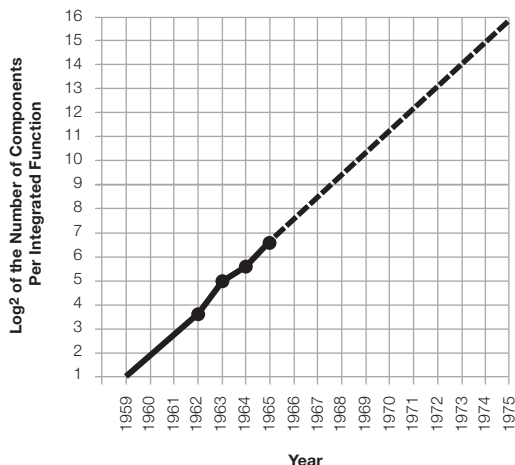
systems out of smaller functions, which are separately packaged and interconnected. The availability of large functions, combined with functional design and construction, should allow the manufacturer of large systems to design and construct a considerable variety of equipment both rapidly and economically.

Linear circuitry

Integration will not change linear systems as radically as digital systems. Still, a considerable degree of integration will be achieved with linear circuits. The lack of large-value capacitors and inductors is the greatest fundamental limitations to integrated electronics 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 integrated electronics is obvious from the terms themselves. Certain resonance phenomena, such as those in piezoelectric crystals, can be expected to have some applications for tuning functions, but inductors and capacitors will be with us for some time.

The integrated r-f 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 be changed 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 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, for example, using a multiplicity of integrated microwave power sources, could completely revolutionize radar.

Excerpts from A Conversation with Gordon Moore: Moore's Law

Moore's Law

Gordon Moore: The original Moore's Law came out of an article I published in 1965 this was the early days of the integrated circuit, we were just learning to put a few components on a chip. I was given the chore of predicting what would happen in silicon components in the next 10 years for the 35th anniversary edition of "Electronic Magazine". So I looked at what we were doing in integrated circuits at that time, and we made a few circuits and gotten up to 30 circuits on the most complex chips that were out there in the laboratory, we were working on with about 60, and I looked and said gee in fact from the days of the original planar transistor, which was 1959, we had about doubled every year the amount of components we could put on a chip. So I took that first few points, up to 60 components on a chip in 1965 and blindly extrapolated for about 10 years and said okay, in 1975 we'll have about 60 thousand components on a chip. Now what was I trying to do was to get across the idea that this was the way electronics was going to become cheap. It wasn't true of the early integrated circuits, they cost more than the bits and pieces that you could assemble cost, but from where I was in the laboratory, you could see the changes that were coming, make the yields go up, and get the cost per transistors down dramatically. I had no idea this was going to be an accurate prediction, but amazingly enough instead of ten doubling, we got 9 over the 10 years, but still followed pretty well along the curve. And one of my friends, Dr. Carver Mead, a Professor at Cal Tech, dubbed this Moore's Law.

So the original one was doubling every year in complexity now in 1975, I had to go back and revisit this... and I noticed we were losing one of the key factors that let us make this remarkable rate of progress... and it was one that was contributing about half of the advances were making.

So then I changed it to looking forward, we'd only be doubling every couple of years, and that was really the two predictions I made. Now the one that gets quoted is doubling every 18 months... I think it was Dave House, who used to work here at Intel, did that, he decided that the complexity was doubling every two years and the transistors were getting faster, that computer performance was going to double every 18 months... but that's what got on Intel's Website... and everything else. I never said 18 months that's the way it often gets quoted.

Interviewer: So just to be accurate, it's two years?

Gordon Moore: Two years in this day in age, and we're doing a little better than that.

Interviewer: 40 years later? Be true?

Gordon Moore: Of course, that was my plan from the beginning, no you can never see that far down the road in this sort of thing. When Intel was founded the entire semiconductor business worldwide was about two billion dollars... now it's kind of 200 billion dollars. The entire market has grown about 100 fold in that time. There was no way we could predict very far down the road what was going to happen. It was just a lucky guess, I guess on my part... lucky extrapolation.

Interviewer: What are your thoughts now, knowing its significance?

Gordon Moore: It's important to certainly change. Initially, just an observation an attempt to predict this was a way to cheap electronics... but the industry made it a self-fulfilling prophesy now, the industry road maps are based on that continued rate of improvement, various technology nodes come along on a regular basis to keep us on that curve, so all the participants in the business recognize that if they don't move that fast they fall behind technology, so essentially from being just a measure of what has happened, it's become a driver of what is going to happen. Something I never would have imagined initially.

Interviewer: How long can it continue?

Gordon Moore: I think Moore's Law will continue as long as Moore does anyhow! Ha ha ha... I'm periodically amazed at how we're able to make progress. Several times along the way, I thought we reached the end of the line, things taper off, and our creative engineers come up with ways around them. I can think of at least 3-4 things that seemed like formidable barriers that we just blew past without any hesitation and in fact, the board meeting we came up I saw pictures that go a couple of generations beyond anything I had seen previously in regards to the highest transistors we can build... so I think we've got quite a bit of life yet. I've never been able to see beyond the next three generations of technology. Three generations of technology is about 6-8 years and I can see that far now, things haven't really changed. Eventually they're going to have to. Materials are made of atoms, and we're getting suspiciously close to some of the atomic dimensions with these new structures, but I'm sure we'll find ways to squeeze even further than we think we presently can.

Past and future

Interviewer: Reflect on 36 years... Thoughts as look back on entire career? Founding greatest companies in the world?

Gordon Moore: It sure is nice to be at the right place at the right time. I was very fortunate to get into the semiconductor industry in its infancy. And I had an opportunity to grow from the time where we couldn't make a single silicon transistor to the time where we put 1.7 billion of them on one chip! It's been a phenomenal ride... if you measure the industry in terms of the number of transistors it makes which I like to do occasionally, there's no industry that I can identify that is remotely comparable in how it's expanded over that period of time. We've grown a lot in dollars but we've grown a heck of a lot more in our output.

Message to employees

Gordon Moore: First of all, I thank them for the contributions they made because really it is our employees who got us where we are today... and are going to take us where we want to go in the future.