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Selected Aspects of Microelectronics Technology and Applications: Custom and Semi-Custom Integrated Circuits*

prepared by

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Summary

Almost all new industrial technology as well as research results on which such development is based originates in the advanced, highly industrialized countries. This is more true for the electronics sector than for any other industrial sector. Furthermore, electronics in all its manifestations has become a pervasive technology affecting all aspects of the society. The catchwords for this process include office automation where computers, wordprocessors and facsimile are key components, and computer integrated manufacturing in which robots and numerically controlled machine tools have become integral parts.

The integrated circuits are the fuel of this electronification process. Companies and governments in the industrialized countries are constantly engaged in a competitive battle to have access to the latest IC technology for defense and civilian applications. A much more limited number is competing in the IC manufacturing technology.

Many ICs have become commodity products and the users are now increasingly turning to application-specific ICs (ASIC) which often promise improved functions and an ability to control the characteristics of a product. The ASICs at the same time provide developing countries and smaller companies anywhere with the opportunity to get access to their specific ICs. This development has been triggered by the tremendous costs for a production line for standard circuits. There are several technical approaches which are discussed in the paper. A logical solution is often to completely separate the design from the production function.

However, the access to advanced technology and use of advanced products is not relevant unless there is a market and most developing countries, except the biggest ones, are still in a very underprivileged position. However, certain emerging markets may provide the stepping stone for entering into the new technological domain and the expanding telecommunications sector is one of them.

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Introduction

Technology strategy and technology competitiveness are words of honor in government agencies and in company headquarters in every industrialized country. This concern is fuelled by the ever closer integration of the world economy and the associated shortening of product cycles. The attention given to staying at the technological frontier is in no little way heightened by the competitive relationship which prevails among the three regional markets - the USA, Western Europe and Japan.

The use of technological resources to maintain superiority is not primarily directed at developing countries or companies in developing countries. However, the technological race in industrialized countries has far-reaching consequences in all other countries and pose very serious policy questions for all developing countries. What kind of technologies should be mastered? What kind of resources are required? What are the possibilities for collaboration? At what technological level should the entry be done? This report will not provide answers to those questions, but rather highlight the technological change which is taking place.

Naturally, there are many shortcomings in a brief report as this one , which has been prepared in a fairly short period of time. First, it has only marginally been possible to incorporate the experience of developing countries.

Second, the report still lacks in understanding of options available to developing countries. Third, the search for material for this report has been rather comprehensive, but the facts and implications have not been checked with experts in the field. Finally, we want to apologize to the authors of all sources for lack of detailed references which have been utilized in preparing this report.

This document divided into three parts. The first part gives a general description of technological resources controlled by industrialized countries. The second part deals specifically with integrated circuits and the final part contains a tentative discussion of the policy implications for developing countries, based on the description and analysis in the earlier parts of the document.

TECHNOLOGY RESOURCES AND TECHNOLOGICAL DEVELOPMENT*

Almost any developing country can establish itself in food-processing and garment manufacture. Many countries can set up their own modern steel complexes and still a fairly large number of countries can create industries to manufacture modern transport equipment. Machinery and technical assistance may be required from abroad but in the end, after a period of consolidation, the industries in many developing countries establish themselves as serious competitors to manufacturers in the advanced countries.

Today, almost all new industrial technology as well as research results on which such development is based originates in the advanced, highly, industrialized countries and this is more true for the electronics sector than for any other industrial sector. This, in fact, has meant that the advanced countries today have a virtual monopoly of the resources required for the development of certain key elements like electronic components, many types of computers, test and measurement equipment and most industrial electronic equipment. The same is generally true for large scale

*) Based on "Forces of Technological Change", in Technological trends and challenges in electronics. Dominance of the industrialized world and responses in the Third World. Edited by Staffan Jacobsson and Jon Sigurdson, Lund: Research Policy Institute, 1983.

systems incorporating electronic technology like telecommunications equipment. The developing countries' share of the global production of electronics production is in the region of 5-10 %. So, a technological gap has been created between developing countries and industrialized countries in the area of electronics. Some of the more advanced developing countries and the bigger ones with a larger resource base like India and China are attempting to break the monopoly of the industrialized countries although with limited success so far.

The technological gap in electronics, which appears to be widening in applications, is not a new phenomenon. However, the gap at the end of World War II between the then industrialized countries and the rest of the world is on the whole likely to have become wider today. When discussing the gap today one can use measures such as trade in high technology products, time lag between production of certain key components etc. - all of which indicate a widening gap not only in participating research and development but equally notably in applications of electronic technology.

In the application of high technology products like computers, telecommunications and highly automated manufacturing processes the developing countries bent on industrializing may have to accept to be totally incorporated into a global economy dominated by the industrialized countries and a limited number of multinational companies based in the same countries.The reason for this would lie in the fact that an increasing number of industrial processes rule out technological choices because of efficiency and quality requirements - unless the production is entirely geared to a domestic market.This would in fact mean that the rich countries would spread their industrial mono-culture the world over and that few if any developing countries would be in the position to escape this influence.

Underlying this change of globalization and technology dominance by the industrialized countries are a number of conditions or forces which should be analyzed and understood.

First, the speed of technological change appears to be increasing. However, much of the technology embodied in new electronics products originated 10 or 20 years ago and what we perceive to be a rapid change of technology is actually the very rapid application of that existing body of technology. So we are now moving along the very steep phase of an S-shaped curve which will eventually taper off with the result that electronics will eventually become a more mature and stable technology. The present situation favours countries or companies which control assets like development resources, management competence and efficient organization for rapid industrial restructuring and market penetration. Such resources are mainly concentrated in the industrialized countries.

Second, there is a shift in the use of global R&D resources with a diminishing share of resources partly offset by the present US expansion - although increasing in absolute terms - going to national defence and an increasing share being controlled and utilized by large companies almost all of them multinational companies (MNCs) based in industrialized countries.

Third, technology development projects are becoming more and more costly. This has led many companies to pool their development resources in areas such as computers, aircraft manufacture and robots which is a pattern of cooperation long followed in the manufacture of complex military systems. The emergence of technology sharing is explained not only by a need to share and reduce development costs but also by a desire to avoid the risks of being cut out of rapidly changing markets.

Fourth, the barriers to entry in many high technology sectors are increasingly becoming more difficult to climb because the minimum scale of operation is increasing. This means that only countries with sufficiently large markets or ability to rapidly develop export markets can venture into certain product lines.

In the descriptive parts to follow, we will accordingly analyse this situation and why it appears to present difficulties for developing countries. The explanation for this can be found in the three major factors: (1) control over R&D resources, (2) the interest of key actors at the four levels - nation, multinational companies, trade unions and consumers - in the industrialized countries, (3) the emerging trends for economies of scale, market control and technology sharing. However, major parts of this report are concerned with technological trends in integrated circuits - in particular custom and semicustom ICs - and consequences for developing countries.

In order to initially provide a proper perspective on the dominance of the industrialized countries it is necessary to look at the global distribution of research and development resources. According to UNESCO statistics, all developing countries combined had in 1980 less than 11 percent of all scientists and engineers engaged in research and development the world over - a situation which most observers agree, has not changed dramatically.

The share in research and development manpower is considerably larger than their share in global industrial production. See Table 1. However, comparing the financial resources - which may be a more relevant measure because of the increasing importance of equipment and instruments -- the developing world's share decreases to less than 6 %. See Table 2.

Table 1

Estimated number of scientists and engineers engaged in R&D for 1980

Continents, major areas and groups of countries	estimated number	estimated number per million population
World total	3,756,100	843
Africa	40,312	86
America	765,661	1,247
Asia	702,920	271
Europe	839,473	1,731
Oceania	33,889	1,472
USSR	1,373,300	5,172
Developed countries	3,359,102	2,875
Developing countries	396,998	121
Africa excluding Arab states	16,387	45
Asia excluding Arab states	693,659	273
Arab states	33,686	206
Northern America	674,725	2,679
Latin America & the Caribbean	90,936	251

Source: Statistics on science and technology. Extracts from UNESCO statistical yearbook 1985.

Table 2

Estimated expenditure for R&D for 1970 and 1980

in US dollars

Continents, major areas and groups of countries	Year	Estimated amount (in million US$)	As % of GNP
World total	1970	62,101	2.04
	1980	207,801	1.78
Africa	1970	188	0.34
	1980	1,156	0.36
America	1970	28,118	2.28
	1980	70,391	1.94
Asia	1970	4,572	0.99
	1980	31,230	1.08
Europe	1970	15,739	1.70
	1980	70,649	1.79
Oceania	1970	497	1.10
	1980	1,953	1.11
USSR	1970	12,987	4.04
	1980	32,421	4.67
Developed countries	1970	60,677	2.36
	1980	195,377	2.24
Developing countries	1970	1,424	0.30
	1980	12,424	0.43
Africa excluding Arab States	1970	105	0.33
	1980	698	0.36
Asia excluding Arab States	1970	4,540	1.02
	1980	30,661	1.18
Arab States	1970	115	0.31
	1980	1,027	0.27
Northern America	1970	27,620	2.59
	1980	66,646	2.33
Latin America & the Caribbean	1970	498	0.30
	1980	3,745	0.49

Source: Statistics on science and technology. Extracts from UNESCO statistical yearbook 1985.

The manpower and finance in research and development is used for a multitude of purposes in many sectors including public health and medicine, agriculture, social science and defence. For some research activities although carried out in the industrialized countries there is less bias in favour of these countries which is partly true in agriculture and medicine. However, even in such fields, research priorities and the underlying assumptions or the required infrastructure will often bring results which favour the rich countries.

While universities in the western world are the main location for basic research, corporations concentrate their research and development activities on turning knowledge into goods and services. A limited number of sectors, aerospace, electronics, chemicals, drugs, motor vehicles, machinery and instruments are financing and controlling most industrial research and development resources of which the development part constitutes an overwhelming 80-90 percent. These sectors accounted in the past for more than 80 percent of total industrial research in the United States and the situation has not yet changed very much and is very similar in the other OECD countries which include Japan and western European countries.

All developed countries together control 94% of the global financial resources for research and development. Two thirds of this is industrial research where the multinational corporations are the dominant actors. They, almost all of them based within the OECD countries, are responsible for an estimated two thirds of industrial research within the OECD countries which equals at least 45 percent of the global R&D resources. See Table 3.

Table 3

The role of the multinational companies (MNC) in global research - An Estimate

	US$ billion	Share (%)
Total Global Research (1980)	208	100
- in developed countries	195	94
- in industry (in developed countries)	130	63
- in MNCs (mainly based in the OECD countries)	93	45

Thus, these companies which include all the familiar names like General Motors, IBM, Siemens, Dupont, Xerox and more recently Hitachi, Nippon Electric and Mitsubishi in Japan, etc. today control an estimated one-third of the global research and development resources. This share has increased over the past 15-20 years and appears to go on increasing. Almost all those multinational companies which have considerable R&D resources at their disposal are in their activities only marginally constrained by national boundaries and national considerations. These companies operate internationally and identify and develop potential products and markets which are overwhelming in the already industrialized countries. Consequently, the characteristics of the developing countries are often not considered as their markets have only a marginal influence in the technological strategies of these international companies.

It must be recognized that the manufacturing plants of the multinational corporations are located in many countries and that diffusion and technology-sharing may occur. However, generally most MNCs maintain a tight control over their technology which is a logical outcome considering that resources invested in technological development is becoming an increasingly larger and more critical share of total investment. Consequently, these companies are little interested in selling their technology, unless they gain access to markets, or new technology from an equal partner. But even if multinational corporations do not relinquish their control over high technology they still contribute to the creation of a more intangible "technology culture" in most countries. This is achieved through familiarity with devices and by transferring skills for servicing, maintenance etc.

The strategy of strict control over technology may be less relevant for smaller independent companies which have difficulties in exploiting superior technology as they are deficient in management and/or resources for the costly stages in product development and market penetration on a worldwide scale. Such companies are then less committed to maintain full control over new advanced technologies, which they may have developed. Consequently, they are more open to sell their technology to buyers in developing countries. On the other hand the same companies are also likely to be taken over by the major MNCs in order to complement their range of new technologies. It must also be observed that linkup to transfer technology from an independent company to a buyer in a developing country may pose certain difficulties because the independent company may lack some of the expertise which is essential in the technology transfer. As a consequence one can expect a growing concentration of resources for technological development in a smaller number of increasingly international-oriented multinational corporations.

IC MARKET AND ELECTRONICS INDUSTRY

Nowadays everybody is aware of the tremendous technological development in microelectronics which has taken place since the transistor was invented in 1948. However, not so many people are fully aware of the fact that this course of technological development is still far from reaching its end. Scientists and production engineers in the VLSI sector are presently discussing the structure of the manufacturing technology for integrated circuits including hundreds of millions of transistors on a single chip. There is little doubt that future technological evolution will fuel dramatic changes in the global industrial structure. It is also apparent that most developing countries as indicated are completely outside the mainstream of controlling, or even participating in this technological development. Three main reasons for this situation can be mentioned.

First, almost all the required resources such as trained engineers and scientists, advanced laboratories and sophisticated markets, are in the hands of the advanced industrialized countries. Second, the development efforts have shifted from the manufacturers of chips to the manufacturers of VLSI equipment, or rather to a partnership between the two sets of manufacturers which raise the barriers for participating in frontline technology development. Third, in order to intervene and become a partner in the IC industry it is necessary to have a substantial home market and only few developing countries have this important asset. Those DCs with big and/or relatively well developed markets for integrated circuits have yet to mobilize their markets for the purpose of developing an indigenous capability in VLSI manufacture.

In 1983 the global production of semiconductors reached more than 17 billion US dollars. The production increased to more than 26 billion in 1984 and decreased slightly in 1985. This value amounts though, to roughly 5% of global production of electronic products and only a fraction of total production value of all manufacturing sectors.

However, the importance of the semiconductor sector far exceeds the actual value of the products. This sector constitutes what could be termed a pervasive technology with far-reaching consequences for most other industrial sectors and the society as a whole. Thus, the semiconductor sector has attracted much attention from policy makers all over the world. (The semiconductor sector includes discrete devices as well as integrated circuits and in recent years the interest has increasingly focussed on the latter ones.) In the early stages of developing integrated circuits it was possible even for small companies to enter into production. This situation has now changed drastically due to the rapidly increasing level of integration and investment costs for the production lines of the advanced circuits. Furthermore, the manufacturers of electronics systems which are based on functions contained in the integrated circuits have come to realize that they have to control the design of the circuits themselves if they are to maintain control over their products. This has set the stage for a very rapid development of custom and semi-custom integrated circuits.

In order to get a perspective on the application specific integrated circuits (ASIC) industry we will provide some general statistics on the electronics sector. The global market for ASIC which includes all semi-custom and full custom integrated circuits was US$1,645 million in 1984, according to the annual review in <u>Electronics</u>. Another source, closer to the industry, states that the production value was close to US$ 2,500 million.[1]

The global production of all electronics products amounted in 1985 to roughly 500 billion US$. Close to one half of this originated in the USA. The major product areas, constituting roughly two-thirds of all production are computers, military equipment and communications. East Asia has already overtaken Europe in importance not only for consumer electronics but also for integrated circuits and it has a considerable higher growth rate than North America and Europe. See Table 4.

Table 4
Worldwide production of electronics equipment
(billions of dollars)

Region	Amount (% of total) 1983		Amount (% of total) 1988		Average Annual Growth Rate 1983-1988
Total	$360	100%	$782	100%	16.8%
North America	163	45	317	41	14.2
West Europe	68	19	131	17	13.9
East Asia	80	22	230	29	23.7
Rest of world	49	14	104	13	16.2

Source: Electronics Week, January 1, 1985 p. 62.

Over the past couple of years it has been argued that semiconductors would constitute an increasingly higher percentage of the production value of electronic products. However, recently available statistics appear to contradict such an assertion. The major reason for this is the fact that the cost of integrated circuits is falling drastically. Consequently, the value of semiconductors appears to remain around 5% in spite of the drastically increased number of functions which are incorporated in almost all electronic products. See Tables 4 and 5. There is presently no indication that this percentage would undergo any major change in the near future.

Table 5
Worldwide semiconductor market
(billions US dollars)

Category	1983	1984	1985	1986	1990
Semiconductors, total	18,153	26,935	28,799	31,855	55.0-75.0
Integrated circuits	13,535	20,979	22,867	72,867	47.0-63.0
Discrete	4,618	5,956	5,932	6,324	8.0-11.0

Source: Electronics Week, January 1, 1985, p. 63.

The total market for semiconductors was in 1985 US$28.8 billion, according to estimates prepared by Electronics. See Table 5.

Table 6

Worldwide market for selected semiconductor devices

(billions of dollars)

Worldwide market for selected semiconductor devices
(billions of dollars)

Category	1983	1984	1985 (Estimated)	1986 (?) (Estimated)	1990 (Estimated)
MOS memory, total	$4.020	$5.790	$6.510	$7.540	$18.000-28.000
DRAM	1.980	3.010	3.350	4.000	10.000-13.000
SRAM	590	1.000	1.150	1.300	2.000- 4.000
ROM	520	530	560	540	1.000- 3.200
EPROM	850	1.040	1.130	1.300	3.000- 5.000
EEPROM	80	210	312	400	1.000- 2.200
Microproc. total	$1.900	$2.900	$3.680	$4.250	$ 8.000-13.000
Microproc. units					
8-bit	900	1.180	1.340	1.350	1.000- 2.200
16-bit	290	440	550	690	2.000- 3.000
32-bit	-		30	80	300- 1.200
Single-chip	550	880	1.100	1.300	2.500- 3.300
Others	160	400	660	830	2.200- 3.300
Stand. logic, total	$2.950	$4.670	$5.210	$5.720	$ 6.300- 9.200
Bipolar	2.400	3.860	4.280	4.700	5.500- 6.000
CMOS	550	810	930	1.020	1.800- 3.200
Full custom	$ 700	$ 880	$1.200	$1.320	$ 2.000- 3.000
Linear	$2.700	$3.600	$3.780	$4.200	$ 6.000-10.000
Power	$ 800	$1.040	$1.110	$1.170	$ 2.000- 3.000
Semi-custom, total	$ 560	$ 780	$1.290	$1.730	$ 2.700- 5.400
Gate array	355	490	730	900	1.000- 1.900
Standard cell	45	75	160	360	1.000- 2.500
Fused	160	220	390	170	700 1.000
TOTAL	18.153	20.925	25.700	31.556	55.000 75.000

Source: Electronics Week, January 1, 1985, p. 64.

Most of the production consisted of integrated circuits which totalled 22.8 billion in the same year. The same journal provides also a breakdown for selected semiconductor devices. See Table 6. This table shows that full custom and semi-custom ICs are of equal importance in terms of market value although it is expected that the production of semi-custom ICs will increase much more rapidly.

Presently, custom and semi-custom integrated circuits are the fast growing items in all major industrial countries. Available evidence indicates that the share of the global market for ICs would increase from about 5% in 1984 to about 10% of all integrated circuits in 1990. It has often been argued that the production of custom and semi-custom devices is suitable for specialization for small firms and by implication for small firms in small countries. Thus, there may be larger possibilities for developing countries to gain a foothold in the semiconductor industry by entering into the market of semi-custom integrated circuits. We will now explore tentatively the basis for such a niche strategy.

A recent OECD report argues that the perception of a niche stratgey is becoming less relevant to some extent. This is due to the development in product and process technology resulting from the emergence of new semi-custom devices - of which gate arrays and standard cells with the associated computer-assisted-design (CAD) systems are the most important.

IC TECHNOLOGY

In order to understand the future role of semi custom integrated circuits and the limitations imposed on developing countries, it is essential to have an understanding of the technological development in the manufacturing process for integrated circuits and the driving forces behind this development. The level of integration increased from a few transistors on a single chip in the early 1960s to around one million in 1985. Much of the underlying change in the technology has, until recently, been driven by the manufacturers of integrated circuits. Nowadays the driving forces of technological change for IC manufacturing technology are taken over by the equipment manufacturers.

In a seminar paper published in 1983[2], Prof Meindl argues that the possibilities for cramming even more transistors on a chip are far from exhausted. In his concluding remarks he states that the rate of progress towards the hierarchy of limits governing Ultra Large Scale Integration (ULSI) was extremely rapid during the 1960s and early 1970s. The present generation of 256 K RAMs has minimum feature sizes ranging from 1.3 to 2.5 micrometers. The minimum feature size is usually defined as the average of the width of the electrical conductors that connect transistors and the spacing between the conductors. ULSI circuits will reach minimum feature sizes of 0.25 micrometers by the end of the century, said Meindl, and possibly even smaller later on.

Meindl further suggests that a perceptible decrease in this rate has been observed since the mid 1970s and is projected to continue until the early 1990s. Theoretical limits on minimum feature size and practical limits on lithography predict a further rate of reduction at that time. Nevertheless, Meindl expects that ULSI chips incorporating several hundred millions of components will be realized by the year 2000. Analogical limits suggest a continued high level of utilization of silicon ULSI as well as rapid advances and volume applications of complementary technologies. Finally, Prof. Meindl concludes that although these projections are quite encouraging, they are limited to extrapolation of already identified trends. The possibility of fundamental new discoveries and inventions can only add to future prospects.

Meindl is careful when arguing about the constraints which set the hierarchy of limits which govern the trends in ULSI technology. The levels of this hierarchy can be codified as * fundamental, ** material, *** device, **** circuit and ***** system.

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* **Fundamental limits** are immutable laws of nature, they cannot be changed.

** **Material limits** are specific to composition but do not change frequently in practice. Silicon has been the keystone material of integrated electronics for the past two decades and this is unlikely to change during the coming twenty years.

*** **Device limits** depend upon both the material properties and configuration of VLSI components.

**** **Circuit limits** are unique because they retain both a complete physical description and a definition of the information processing function of a group of components and interconnections. Moreover, circuit limits describe device performance in a realistic operating environment and not in sterile isolation. Consequently, the circuit level of the hierarchy is the most appropriate one for projecting the smallest allowable dimensions of ULSI structures for specific purposes.

***** The **system** level of the hierarchy can be expanded into several discrete steps reflecting the logic design, architecture, instruction set, algorithms and application of a particular ULSI configuration. System limits are the most numerous and nebulous set of the hierarchy. However, since opportunities for integration at each of the five hierarchical levels are constrained by the limits of all preceding levels, system limits represent the most profoundly important set.

In a commentary in Science,[3] Meindl's projections are claimed to bracket a range of chip densities corresponding to minimum MOS transistor feature sizes from 0.5 to 0.25 micrometer. In this article, Robinson is more far reaching in his projections and claims that the smaller number will lead to about 1 billion transistors per chip by the year 2000.

Meindl also discusses the practical limits to the future high levels of integration. He claims that theoretical limits are based upon the principle of solid state science whereas practical limits depend upon manufacturing processes and equipment. The status of the five levels of practical limits that constrain ULSI can be summarized in terms of three parameters: minimum feature size, die area and packing efficiency. Meindl notes that theoretical studies have established limits on minimum feature size but similar limits on die area and packing efficiency have not yet been defined.

If the above-mentioned trend is to take place during the nearest twenty years, tremendous changes in the equipment used are to be made. Mr Bottoms, from one of the equipment companies (Varian Associates), argues that the driving forces for these changes are all economic. Shrinking geometries will allow increased device speed, and the same number of devices, if faster, yield more electronic functions. Reduced device power consumption, more circuit functions per unit area, and reduced silicon defect and particulate related yield loss are also benefits of reduced geometries. Finally, one of the most advantageous factors is that as the scale of circuit integration is increased, system costs are reduced.

In one of Bottoms' articles it is stated that "It is expected that there will be more major advances in solid state technology in the next decade rather than in the last. These will be driven primarily by advances in equipment than by advances in device design".[4]

The following presentation is based on the above mentioned article by Mr Bottoms. He states that there is a considerable premium for higher levels of integration. A few years ago computer manufacturers were asked how much they would pay for a 64K circuit compared to a 16K circuit. The answers ranged from three to five times as much per bit. This meant that the cost of interconnection between integrated circuits had more leverage than the cost of the ICs themselves. However, statistical evidence from IC markets indicates that the price of IC dropped so rapidly that 64K circuits became available within 3 years at the price of 16K circuit. The same is true for 256K compared with a 16K circuit.

To make further developments possible, some fundamental limitations of production technology have to be overcome. Bottoms discusses, among other things, the limitations in three areas: lithography, etching and high temperature processing.

Lithography

One limitation to further die size reduction in lithography is to be found in the resolution capability of the equipment itself. The second limitation is overlay accuracy. Small geometries can presently be achieved in many ways, but unless overlay large patterns are compatible with these geometries, they cannot be used for building VLSI devices. Finally, resist processing must be improved. Resist technology must be compatible not only with lithographic requirements, but also with the subsequent process steps, whether they be etching, implantation, or steps requiring high temperature.

Bottoms writes that there are several new patterning technologies that will compete to solve these problems for submicron devices. The first one is the technology presently used - optical direct step-on-wafer. By using deep ultraviolet illumination, submicron device production can be achieved with this equipment. It is used for a limited number of leading edge devices, but it has now reached its fundamental physical limit. Manufacturers are running out of resolution and of the ability to operate with a reasonable depth of focus. A technology which will solve both the resolution and depth of focus problems is x-ray lithography. This technology is in the development phase, but the only current production application for x-ray lithography is in single-critical-layer devices like magnetic bubble circuits.

Bottoms states that Focussed Ion Beam (FIB) systems offer the possibility of eliminating lithography for any of the steps that involve doping since the FIB can dope directly without having to go through the intermediate steps associated with oxidation, patterning or etching. However, FIB is unlikely to be a cost effective patterning technology, at least during the present decade. Finally, direct write electron beam lithography is a technique which is very close to commercial availability and it will solve the resolution, depth of focus and overlay accuracy problems.

Etching

In his discussion of etching, Bottoms mentions that this is the next limiting process for VLSI manufacturing. Several parameters must be satisfied:

(1) Selectivity is required to etch one layer without damaging the underlying layer.
(2) Control of the degree of anisotropy is necessary so that a tapered wall or a straight side wall may be achieved, depending on the particular process and the requirements for that process step.

Bottoms also emphasizes that uniformity is necessary since selectivity is not perfect.

The final limitation in etching is cost. It is still more expensive to etch many materials with dry etching than with competing wet etch technology. Many systems being used today are batch systems that do not lend themselves well to the automation we need in order to meet the objective of high yield, very large scale integrated circuit manufacturing. t is probable that new processes will have to be developed in order to accomodate the requirements of automation.

It is currently absolutely necessary to have a high degree of film thickness uniformity as devices and wafers get larger and etch selectivity remains less than perfect. In the past, achieving adequate step coverage was not difficult. Now it is necessary to cover one micron steps on a one micron pitch, and with a side wall coverage we never dreamed of with earlier technologies. The conductivity that is demanded of interconnect material is now greater since increasing circuit sizes are being accompanied by smaller cross-sectional areas of connecting lines.

High temperature processing

High temperature processing poses yet another problem. Bottoms writes that a limiting factor for VLSI production is the number of processing steps that require the silicon to reside at a high temperature for an extended period. Current processes will not be satisfactory for submicron circuits. There are also some materials that manufacturers would like to use but that are not yet compatible with high temperature processing. The inability to use those materials may limit progress with multilayer interconnect and other promising new areas for IC development.

The article on submicron VLSI production indicates some of the projected changes. The author mentions that the following new technologies can be expected:

1. Focussed ion beam systems can do many things such as three dimensional interconnect deep in the circuit and customization of circuits by buried layer implantation in defined regions.
2. Direct CAD e-beam links and direct CAD links to other processing and test tools, including direct computer access to automatic testing systems, promise tremendous improvements in new design turnaround and engineering productivity.
3. Low temperature epitaxy is a process of increasing importance that has not yet been automated to a satisfactory level. Epitaxy is presently a big particle producer. It is a batch process and it is difficult to control.
4. Ion implantation has successfully generated dielectric isolation as a part of VLSI technology, but not at a speed that would allow it to be commercially interesting. Processes for buried dielectrics are in need of further development.
5. Increased density will also be achieved with multilayer interconnects. Two and three layer-connects are being

used today, but five, six or seven layer-connects are expected in the near future to allow systems integration with redundancy built in, without going to off-chip interconnect.

6. Wafer-scale integration, combining many of these technologies, will enable larger circuits with much greater computing power. Substantial increases in system speed will be realized by reducing intercircuit propagation delays.

Finally it is also necessary to consider automation, otherwise the discussion of the production requirements for VLSI technology would not be complete. In order to be able to produce circuits with smaller features and with acceptable yields, people must be removed from the fabrication process. One of the reasons for this is that people generate a major percentage of particulate contamination. Also, slight variations in operator procedure from lot to lot and outright operator errors are significant detractors from process yield. VLSI trends to increasing process complexity, decreasing tolerance of process variations, and shorter production runs will exacerbate these problems.

Bottoms states the following about automation:

> "The economics of automated material handling and automated process control is very straightforward. Reduced operating expenses result not only from reductions in direct labor (in fact, labor is only a small part of it) but from energy and raw material input. Requirements for indirect labor are reduced and productivity of process engineers and maintenance crews is increased. The greatest single advantage of automation is the increased output resulting from improved line and probe yield and reduced rework."

In the late 1970s, the VLSI industry had a steep learning curve due to the reductions in linewidths which enabled the increasing level of integration.[5] Both defect density and linewidth reductions reduced the cost of manufacturing DRAMs. Such circuits will probably be one of the first subjects for automated manufacture and they are also high volume commodity items. It is clear, though that the technology that will take the ICs through the 1 um barrier needs more time to develop. It is going to take more engineering manpower and more money. The results may be available towards the end of the present decade.

In a commodity market, volume justifies automation. Where linewidth reductions are used to gain improvements in cost, the industry no longer achieves as much momentum as it did, for example, in the early 1970s. This means that even if submicron linewidth technology was available today, it would not buy the industry much.

Hutcheson argues that in general, manufacturing strategies win in the marketplace by providing equal or better quality products at a much lower price. Manufacturing strategies are already well used by companies such as GE and many Japanese semiconductor manufacturers. The key in establishing manufacturing strategy is to develop more cost efficient manufacturing lines.

Hutcheson makes a reference to Henry Ford who used manufacturing strategies quite effectively in the 1920s when he dramatically altered the structure of the automobile industry by developing the automated production line.

Ford's approach accomplished two things. First, it enabled the production of a car at a much lower cost than what was previously possible. Second, and often overlooked, Ford's automation pushed up the capital cost of entering the market with a cost effective line. Only the very large competitors could afford automation. In Ford's case, future growth was insured by locking out new entrants into the market. This is actually what has happened in the semiconductor industry since the late 1970s.

The capital cost for a plant will continue to increase in the future as plant sizes increase. Consequently, the increases in equipment costs will require more efficient utilization. This will give manufacturers more flexibility in trying to produce an automated line. In turn, automation will cut costs by eliminating defects from the process and by making more effective use of resources, such as labor and materials.

In summary, the semiconductor industry is presently spending exponentially more to get smaller decreases in linewidth, but it is not getting anywhere near the kind of decrease in cost that it is used to. The semiconductor industry must look at other ways of reducing the cost of manufacturing. One way is by increasing plant capacity.

Hutcheson argues that there will be two development lines of automation. He states that the same types of automation will not work well for both custom and commodity semiconductor manufacturing. Consequently, it is expected that two types of fabs* will emerge in the future, each with its own characteristics:

Since our report is mainly concerned with custom and semi-custom ICs, we will go into more detail only in the case of the Cinderella Fab.

The "Cinderella Fab" is characterized by the many start ups in the semiconductor industry, as well as captive

* The "Cinderella Fab" (i.e. small-scale fabrication) for custom IC production, and

* The 'Monster Fab" (i.e.) large-scale fabrication) for standard ICs.

manufacturers. Their focus is to turn a customer's design into a working device at "the wave of a CAD terminal". This requires an extreme amount of flexibility. Equipment that is easily and quickly reconfigured to run new products with low tooling cost is thus necessary.

When a new product is designed, the heavy expenses for mask making in time and dollars are often bypassed. The time to produce a new product can be cut literally from weeks to hours. Electron beam direct writing lithography is favored. In these cases, automation within the equipment is intensive. It is also highly software intensive. However, there is little hardware automation between equipment types.

Memory chips have fairly simple designs and they are produced in larger volumes than other types of integrated circuits. Many semiconductor companies master the latest production processes with memory chips and then use those processes also for manufacturing more complex products. Without experience of making high-volume memory chips, semiconductor companies may not be able to produce any kind of chip at a competitive cost. It appears that Japanese companies are presently the most successful ones in marketing the production technology for high volume memory circuits.

One of the key advisors on the government's policy in the elctronics sector in Japan, Professor Tanaka, makes a clear distinction between the development of new technologies and the competence required to apply the development onto production. According to Tanaka, neither USA nor Western Europe have any difficulties in developing new technologies. They are generally far ahead of Japan but they are no longer able to apply those new ideas in actual production - at least not with any considerable degree of efficiency. With reference to 256 K DRAM, Tanaka says that the US companies are able to develop new circuits, but they cannot, however, produce them efficiently. Tanaka stresses that this problem - discrepancy between development and production engineering - will become increasingly serious as the level of integration increases and the manufacturing technology goes beyond the submicron level.

There are several explanations for the gap in development and production between Japan and other industrialized countries. The major change affecting the industrial scene is that production becomes more difficult as the level of integration increases. Then the quality control becomes critical, but this resides in the workers - based on their skills and patience. The discussions among different categories of workers are carried out over and over again. People are very critical this process.

Such differences are, according to Tanaka, going to become increasingly pronounced as submicron technology is becoming more pervasive. This leads to a situation, which probably will not become obvious for a few years, in which Japanese companies will dominate the actual production of new technologies.

Some of the major engineering companies in the Republic of Korea are now attempting to enter the semiconductor field. Tanaka considers that they are facing serious difficulties and the situation is quite complicated. Due to their economic orientation, it has been natural for those companies to turn to the USA. However, due to reasons stated above, US companies are not able to provide good technology for high level integration semiconductors. Therefore the companies in the Republic of Korea are interested in importing technology from Japan.

The investment requirements are very considerable for semiconductor companies striving to keep their factories up to date. The US manufacturers, for example, invested $4.5 billion in 1985. In one article[6] it is mentioned that if chipmakers ran their plants all out, they could fabricate around 4.5 billion square inches of the silicon wafers that are diced into semiconductors. World demand should come to 1.2 billion square inches in 1985, barely more than a quarter of the potential supply.

As a consequence, the rewards of chipmaking have fallen and the risks keep rising. This has led the US semiconductor companies to look for alliances in order to share costs for research and development, marketing and even manufacturing. Some companies will be forced to merge with each other or sell out to big corporations. The situation is slightly different in Europe where big companies like Philips and Siemens already dominate the market. The situation in both Japan and the Republic of Korea is similar to the European case.

Japan is often regarded as the cause for worldwide overcapacity - at least from the horizon in the USA. Since Japanese companies believe that dominating chips is the key to dominating the electronics industry, they have been investing in semiconductor plants at a level which is equivalent to US investments although Japan's production has been considerably smaller.

According to the article in Fortune, Japanese companies allocate 27% of sales into new plants and equipment, vs. 18% for US firms. In 1985, the highly efficient Japanese factories, willing to obtain market shares at a low price, drove almost every US chipmaker, except Texas Instruments and AT&T, out of the $500-million-a-year market for the DRAM (dynamic random access memory) chips used for temporarily storing data being processed by a computer. The Japanese companies also stepped up their attacks on the market for E-PROMs (erasable, programmable, read-only memories), another type of computer memory chip often used for storing software programs. However, more careful analysts argue that the pricing and market power of the Japanese companies are based on advanced production knowledge rather than dumping practices.

APPLICATION SPECIFIC INTEGRATED CIRCUITS (ASICs)

Background

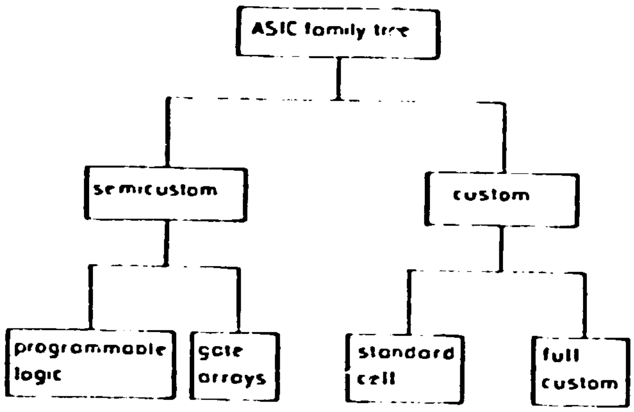
Every three years a new chip generation hits the market and provides a new and higher level of integration. The manufacturing process becomes more complicated and requires increasingly higher investment costs. This is common knowledge to everyone with an interest in the electronics industry. However, the IC industry is also undergoing two other major fundamental changes. First, the development which in the past was mainly fuelled by the chip makers is now increasingly being dominated by the makers of IC equipment. Second, the design of chips is being shifted to systems engineers, i.e. to the makers of products in which the chips are being used. This development, which is one of the foci of this paper, may in fact mean that a new alliance will be merged between makers and users of the chip. In many cases it will mean a new dominance of companies combining the two approaches. In other cases it may mean new possibilities for independent system companies.

Naturally, the companies which use chips want to include more functions required for a certain product onto a single chip, or a set up of chips. In this way it will be possible for these companies to have a higher bargaining power towards the customers as well as higher strength in the market. Integrated circuit content is, of course, a measure of the degree to which VLSI has been applied to handle the problems of a system. Thus, many companies are eager to convert designs into VLSI which becomes much more importnnt than obtaining a good price for an old product which may sometimes become obsolete due to the introduction of competing products. Many companies have an IC content in their products in the range of 5-7% and analysts generally predict that the share will continue to increase.

Quite often, standard chips are not available for specific functions or do not offer the necessary protection of the characteristics of the system. At a lower level of in egration this problem was less critical as many chips could be combined on a circuit board or a number of circuit boards. This approach is still possible but would generally forfeit many of the possibilities which higher integration offers such as high speed of operation and efficiency of the system, its cost etc.

In order to provide a basis for the discussion to follow, we will briefly describe the technological and economic aspects of application specific integrated circuits (ASIC). The ASICs are basically divided into custom and semi-custom circuits and different technologies are used with consequences for production methods. See Figure 1.

Figure I
ASIC family tree



Source: Penn, M.G.: Impact and opportunities for application specific integration circuits. IEE Proceedings, Vol 132, Pts E and I, No 2, March/April 1985.

Components for many types of electronics equipment are used for complex technical functions. With increasing complexity of electronics systems more functions are incorporated in a small number of components. The diversified requirements from systems designers still makes it very difficult for IC manufacturers to provide standardized components which meet the needs of many different users. Furthermore, the chip designer has limited knowledge of systems. Thus, if a system manufacturer wants to use standard ICs he can either transfer his system requirements to a chip manufacturer or wait for a circuit to appear on the market, in all likelihood based on the specifications from a competitor.

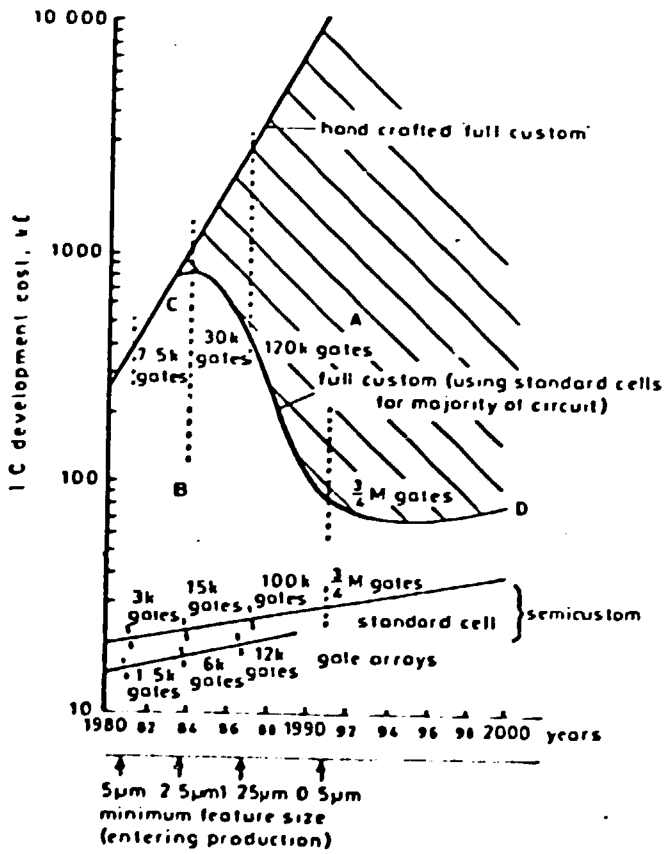
A natural way out of this dilemma is to develop an application specific integrated circuit which can be optionally designed to meet the system specifications of the user and at the same time remain exclusive in order to strengthen the user's position in the market. An efficient solution requires an optimal use of either monolith technology or thickfilm technology.

Monolith technology has been the driving force for the custom circuits which exist today. Most monolith circuits use silicon substrates and the level of integration for digital circuits is generally high. Both digital and analog functions can be integrated on the same chip - an important quality, for example for applications in the telecommunications sector.

Thickfilm or hybrid technology provides another possibility of integrating various components into a functional unit. The base is a ceramic substrate on which connectors are printed and resistors made of thick film. Furthermore, many substrates also include monolithic circuits, transistors and chip condensors. Finetuning of a hybrid circuit has enabled laser trimming of the resistors while checking the functional performance in order to achieve a perfect match with the system in which the circuit is going to be used.

In the past, the efficient solution to a system circuit has involved a choice of both monolithic and thickfilm technology. The optimization of the circuit often extends far beyond the original circuit for which it was designed. The reason for this is that the system designer does not only want to include a maximum number of functions into the circuit, but also wishes to minimize the number of surrounding components and PCB (printed circuit board) area. This clearly indicates that a close relationship between the system maker and the chip maker is needed. The system designer must have good understanding of component manufacture and the chip maker must be able to indicate the technical and economic consequences for various types of specifications. A few years ago it was argued that the development of manufacture of ASICs was a well developed technology made possible by the advanced computer facilities which had become available.

Figure II
Development cost trends of logic ICs against time and complexity



Source: Arnold, J.S.: Trends in application of semiconductor technology. IEE Proceedings, Vol 132, Pts E and I, No 2, March/April 1985.

Naturally, the choice of ASICs is strongly influenced by cost considerations as the fixed costs are high. The costs include not only the design of the circuit, but also the costs for layout, for making the masks and for designing testing programs. Figure II shows the relative costs for various types of ASICs.

By using standard sets of components and only allowing variations in the final mask layers which provide the connections between sets of transistors and the pins, it is often possible to achieve economical production of small series of monolithic circuits. Thus, it is possible to combine the requirements from different customers with modifications only in the final stage of IC manufacture.

In the past, this has enabled economical production of only a few thousand circuits per year. With an annual demand exceeding tens of thousands, it is generally more economical to turn to full custom ICs. Original masks are then generated for each successive layer of the silicon wafer. Costs and time requirements have still remained within limits through the use of computer assisted design (CAD) and the use of standardized cells and rules for mask generation stored in the computer program. An important advantage is the more efficient use of the silicon wafer which reduces considerably the costs for large series. However, when digital and analog functions have to be combined on a single chip, it is usually necessary to adopt the full custom approach. Full custom also dominates the development and manufacture of thickfilm circuits which enables shorter time and lower costs compared with monolithic circuits.

The system designer can choose two different approaches: full custom designs and semi-custom designs which have been discussed in some detail in the earlier part of this section. It is considerably cheaper and less risky to enter into the market for semi-custom chips since they are principally based on standard design. In the past, customization has been a very laborious manual process - similar to that of designing a new chip. It was necessary to use large sheets showing the gates and positions for wiring tracks. This was done by using a pen or plastic ribbon and the results were then put into digitalized form. Two major changes have taken place. The designer can have at his disposal a manual consisting of a library containing a large number of familiar cells. The computer design system contains data on the formation of such cells from the primitive gates of the array. In a way, the process is quite similar to using a high level language to write software for a computer, where the compiler converts the instructions into machine codes. The second important change is the provision of instructions which will provide the routing of arrays with several thousand primitive gates. The actual placement can also be handled automatically. It is argued, however, that the human brain is better adapted than the present-day computers to carry out this task as the human being is still able to consider a wider range of constraints.

Technological choices

Over the past few years there has been a very rapid increase in the design, fabrication and use of semi-custom integrated circuits. The need for the rapid development of custom ICs has been triggered by the systems engineers who request lower costs and higher functionality for their equipment. In many instances it is not the cost of fully custom ICs which has spurred the trend towards semi-custom ICs, but rather the world shortage of experienced IC designers. One of the driving forces for the popularization of semi-custom ICs has been the advances in computer assisted design (CAD) which will be discussed later on in this report. It has been argued that the shift in industry towards customized semiconductor technology may have as profound and significant an impact on the world's electronics industries as the microprocessor revolution had in the 1970s. The custom ICs have been commercially available for more than 15 years, but it is only recently that their use in systems has been applied. Before entering the discussion of semi-custom technology, however, we will offer a few definitions which might prove useful for the following.

In a handbook on components we found the following:[7]

> "A custom integrated circuit is an integrated circuit designed to perform the functions for a single special-purpose application. They can be digital or linear and can fall into any number of technologies. Custom logic circuits can be part of custom families, i.e. families using logic cells that are different from any of the standard cell families, or they can be digital-logic circuits which are fabricated from standard logic cells but perform nonstandard logic functions. It is strongly recommended that design engineers do not, in most cases, pursue custom integrated circuits. A custom monolithic integrated circuits costs between $20.000 and $100.000 in initial tooling and design engineering. This cost must, in the end, be amortized over the application. Careful examination of standard integrated circuits offered on the market usually indicates the availability of a standard circuit that meets the full requirements of the vast majority of applications."

There are basically three types of semi-custom integrated circuits - gate arrays, programmable logic and standard cells. The gate arrays are reported to have made spectacular progress over the past few years but programmable logic has continued to be widely used throughout the electronics industry due to its low cost and ease of programming. Equally important is the continuous advances in computer assisted design. The third main area, the cell based systems, is expected to gain in popularity over gate arrays. The definitions for the two major technologies are given below.[8]

> **Gate arrays** (variants are called programmable and uncommitted logic arrays) are "smorgasbord" chips: they contain just about any ingredient a customer could want, but not all are consumed. Rows of cells, each cell containing a cluster of logic "gates", are grouped on a chip. The cells, and the chips themselves, are proven off-the-shelf designs, but the all-important connections between the cells are left for individual customers to choose. The chip gets its "personality" only when the metal connections are etched on to it during the final stages of fabrication.
>
> **Standard cells** enable designers to decide simultaneously which bits of the chip they want to use and what they will put on the chip. They have to choose between different clusters of logic gates and squeeze them into positions that maximize the chip's ability to do a particular job at high speed.
>
> It is rather like designing a chip from scratch, with one crucial difference: the designer does not have to craft and position every gate - he can mix and match ingredients picked from a bundle of ready-made designs stored in a computerised cell library.
>
> The term ASIC - Application Specific Integrated Circuits - covers all ICs that can be customised to

meet a particular application; it includes gate arrays, standard cells, full- custom circuits and programmable logic arrays.[9] Mr. Penn argued at a recent conference that by the end of this decade, ASICs will account for 23% of the world IC consumption. ASICs account currently for less than 16% of total IC consumption. The captive manufacturers, i.e. those companies whose total IC production is consumed within their own organisations (for example, IBMs), currently account for over half of the total ASIC consumption.[10]

There are three basic block types that one must be familiar with for optimising a system design.[11] The highest level is the array. One can select from a vendor's choice of technology, process, gate and I/O capacity for the array block. The lowest level is the hardware macro, often termed as primitive.

The selection of an array can be a tedious decision. One must choose from several hundred array types that are offered by a multitude of vendors. Different vendors and different arrays offer various options that can be application specific for the individual.

Gate arrays and standard cells

Generically the two computer-aided design techniques now available are known as semi-custom design, and individually as gate arrays and standard cell.

Gate arrays have been around for a number of years, typified by the Ferranti 'uncommitted logic array', which became so familiar that the term 'ULA' has become synonymous with gate array.

The gate array comprises a 'master slice' of silicon processed up to metal, containing all the diffusions for an array of standard gates. Master slices are manufactured in relatively high volume, held in stock and 'customised' as required with a metallisation pattern specified by the user.

Standard cells

With the exception of microprocessors and memories, the merchant companies have produced few standard parts which fully utilise the process capabilities. The reason for this is simple: more complex circuits are more specialised. Thus, whilst development costs escalate on a power-law curve with complexity, the potential market is reduced.

With standard cells there is no master slice, instead, the computer library contains a complete description for each cell extending through all the layers of processing. Each cell is an optimised design produced by experts. Without the limitations imposed by the primitive gates of the gate array, and by providing just as much tracking space as is needed, the chip area is much less than for a gate array. There are, however, penalties. A full mask set is needed and, using a modern CMOS process, the difference is between 3 masks for a gate array and 10 or 11 masks for standard cell. This means that development costs are higher. Furthermore, whereas the metallisation of gate arrays can be carried out in a special unit set aside for the purpose, standard cell production has to slot into the work schedules of a large production facility. This can mean delays in delivery. Moreover, since production batches are typically four times the size of those for gate arrays, there is a cost penalty for small volumes.

From a users's point of view, whilst price reduction of standard parts of modest complexity is nice to have, much greater savings in end product costs can be obtained by using the process capabilities for fewer, more complex devices.

Fully hand-crafted design in the traditional way, where every transistor is tailor-made for the job, becomes rapidly unrealistically expensive and the time scales too long. The lower limit is for the case where the majority of the design uses standard cells from the library. Only special requirements in critical areas need be hand crafted. These circuits can in turn, be designed as standard cells, which are subsequently added to the standard cell library. As the library expands, the lower limit cost for hand-crafted design falls. At the same time, designers in the equipment business using the library can handle more complex design. Eventually the lower limit of costs for hand-crafted design will level off and increase to parallel the standard cell design costs.

Purely economic considerations are not the only reason for choosing standard cell. Unlike the gate array, standard cell libraries can also include analogue functions, for example a range of cells to design switched capacitors and active filters. Other functions such as phase-locked loop, voltage-controlled oscillator, ADC and DAC can also be included.

As on-chip complexity grows, the design process becomes more difficult using only the basic library cells. Some manufacturers are now introducing parametric cells. The final stages in the semi-custom design process of mask making and processing of samples are relatively expensive. Therefore, there must be a high confidence in the design to risk commitment. Unlike a printed-circuit board where some errors can be corrected with cut and strap, a chip that does not do its job is of no use to anybody.

Computer Assisted Design (CAD)

The short-turnround advantage that makes the semi custom IC such an attractive proposition has been made possible by the development of small powerful computer-aided-engineering (CAE) workstations.[12] Mr Watts argues that the popularity of ASICs stems partly from the ability of today's CAE workstations to serve as a total development system for IC design, even leaving the critical layout stage in the designer's hands. Mr Watts states that the functionality of CAE workstations has been expanded to include the same basic tool set for full custom as for semi-custom.[13]

Mr Watts provides the following overview:

> "The introduction of the first computer-aided-engineering workstation early this decade brought the power of CAE directly to design engieners' desks thus enabling them not only to create electronic circuits of any size and application b ut also to verify them."

With the explosion of the full- and semi-custom IC market in recent years, and in order to meet the needs of the associated systems designers, fully interactive CAE workstations have become increasingly important. The IC market explosion was fuelled by system design engineers who required high-performance, low-cost, and compact system designs that are quicker to market and thus maximise investment.

The final hurdle has been cleared by two developments. The first was the utilisation of the same special purpose hardware accelerator originally used for the hundredfold acceleration of the verification tools. This multiprocessor microcoded engine also accelerated the computationally intensive tasks of automatic placing and routing, comparing favourably with mainframe runtime while still giving the designers full interactive control The second development was the running of highly effective algorithms on the microengine, maximising the efficiency of the placement and routing.

The cost of an IC is primarily a function of chip size and volume. Complexity has only secondary effects on costs, provided that one is not pushing ahead of the advancing front of technology. In a review on trends in application,[14] it is argued by Mr Arnold that user designed LSI and VLSI (semi-custom) will both reduce the cost of existing products and encourage new products. He says that the most noticeable impact of new technology will be in home entertainment, in office systems and in engineering aids. The combined effect of VLSI technology, high-density re-usable optical disc recording and low-cost high band-width transmission using monomode optical fibre can turn most imaginative concepts into reality.

The semi-custom revolution offers much more than just cost reduction of existing products. The complexity which is possible with gate arrays is expected to level off at about 15.000 primitive gates, independent of further improvements in semiconductor processes. Arnold argues that standard cell chips can be much more efficiently designed. The standard cell concepts are currently being adopted by the merchant companies for the design of standard parts because the savings in[15] development costs outweigh minor penalties in chip area.

Testing

Facilitating the design of gate arrays has meant that development costs and time scales have been reduced to the point where they compare with a solution with standard parts and a circuit board. There are generally considerable savings in system production such as circuit boards, connectors, shelves, cabinets, wiring and assembly. However, such savings may also be influenced by changes in physical characteristics of the semiconductor circuits, e.g. in the area of packaging technology. It is expected that surface mount technology (SMT) will soon become a major factor in both device packaging techniques and in board and system designs which use integrated circuits. The basic reasoning is quite simple. If the circuit itself requires only 0.7 cm2 why use an area of 5.0 cm2. If the ICs were only slightly larger than the silicon chip itself, the printed board manufacturers would be able to pack more functions on a given board. Naturally, one problem is that different "standards" have proliferated and this makes it more difficult for automatic IC handler manufacturers to supply the needed interfaces for automatic testing equipment.

Testing is a crucial area in the development of ASICs. We will now present viewpoints from two authors[16]. It is generally agreed that the major challenge to test program generation arises from the greatly reduced access to internal circuit nodes as one moves from a printed circuit board (PCB) to a single chip.[17] With increasing complexity, the tedious manual process has tended to become a major bottleneck in the gate array development cycle, diminishing the advantages inherent in semi-custom design. The alternative, automatic test pattern generation (ATPG), has long been recognised as one of the most intractable areas of design automation.

Totton claims that the use of increasingly sophisticated automatic test equipment (ATE) is needed due to the steady growth in the complexity of gate arrays. The cost of such ATE must be amortised over a fairly short lifetime. Therefore, there is some motivation to design integrated circuits which are testable by fairly simple ATE. High pin count and lengthy, unstructured test programs place heavy demands on ATE since in the latter case the programming facilities, e.g. looping, may not be exploited. Wafer probing problems also arise, with circuits having high pin count; the probe card becomes congested and reliable probing of a large number of pads is difficult.

Another expert in ASIC testing argues that after a long period of little communication, CAD/CAE and ATE vendors are beginning to respond to user needs by providing systems that can link the design and test functions. Mr Turino says that the key to that bridge, being touted at present, is the fault simulator. A fault simulator is a software package that evaluates what the circuit being designed should do and what might happen if the circuit contains faults.

It is obvious that increasing integration densities, made possible by advances in wafer fabrication technology, have stretched the capabilities of conventional IC test techniques. The problems are becoming acute on the more complex semi-custom ICs, and even the adoption of structured design techniques enforced by rigid design rules leaves some test issues unresolved.

In order to exploit the denser technologies to produce application-specific circuits cost effectively, new test methodologies will be required, which utilise dedicated on-chip logic to reduce the complexity of the test generation task. Built-in self-test techniques will play an important role in reducing the volume of test data, while maintaining high test quality.

Since many companies move towards custom and semi-custom technology it can be expected that the interface between designer (e.g. customer) and manufacturer/tester (e.g. semi-custom or custom IC supplier) will become even closer in the future than it is today. This trend will imply that even greater attention has to be given to the testing capacity and reproducibility.

Despite the great technological advances, the electronics industry is not yet able to make full use of all the new possibilities offered by the manufacturers of VLSI circuits. One observer argues that the present capability of ICs provides an opportunity to build complex high-performance devices, but the traditional design techniques have become ineffective. The reason given is that the VLSI circuits are becoming as complex as the systems they replace. As a consequence, there are no standards at the system level, as so few systems have been built, to be converted to standards at the chip level. In other words, the ability to put transistors on a chip has outpaced the ability to use the chips.

The memory chips and the complex central processor units (CPU) have achieved a considerable level of standardization. Beyond that it has become very difficult to define standard devices which have a sufficient universal appeal in order to justify mass production. We can expect that in the immediate future the complexity of systems which incorporate VLSI or even Ultra Large Scale Integrated Cicruits (ULSI), will increase as the complexity of the circuits increases. When it becomes more difficult to incorporate the new products into new equipment design, the industry may enter the so-called "applications gap".

A major reason for the application gap is the fact that the manufacturer of systems is familiar with his own needs and has to carry out the development with or without expected developments in IC technology. The rapid development of ASICs clearly indicates the attempts to bridge the gap but it appears to be only a very first beginning and there exists a basic problem to future progress. The designer of chips and the designers of systems have traditionally very different engineering backgrounds. Naturally, the recent tools for ASICs - such as computer aids - have somewhat improved the situation. In essence, semi-custom design presently provides the digital system engineer with a relatively simple, fast, and low-cost route to advance silicon technology. One would therefore expect that computer-aided design would play a major role in all stages in the development of custom chips - given the increasingly higher level of integration. However, this has not yet taken place with the exception of some system designs developed by large computer manufacturers with captive processing facilities. There is little doubt that there are considerable benefits to be reaped by the use of logic simulation in areas such as automated layout and design verification.

We can expect that the successful electronics companies of the future will be those companies which have been able to integrate the design of systems with the design of ICs and thereby able to fully exploit the advantages of VLSI and ULSI. It has been ventured as a guess by many observers that this role of integrating system and chip design will be shouldered by merging design centers. They could then be catalysts for bridging the application gap.

It is far from obvious where this future catalytic activity will be found - with the IC manufacturers, with the system companies or in independent companies. Obviously this has consequences, among other things, for policies to be pursued by developing countries. However, sheer numbers would indicate that a substantial part of the game will be played by the system companies as all the circuits have to be designed. Nowadays there are, at most, 2,500 experienced designers of integrated circuits in the world. However, there are more than 200,000 systems engineers who are potential IC designers. This may in fact indicate a future shift in the control over development of IC technology where the electronics systems companies may increasingly become important actors.

THE EXPERIENCE IN DEVELOPING AN INDUSTRIAL IC BASE

The earlier presentation on IC technology in general and application specific ICs (ASIC) in particular has clearly shown the speed of technological change and the considerable resources required to master the new technology. Consequently, only a limited number of countries are in the position of embarking on a major venture in IC technology. We will briefly discuss the experience of the Republic of Korea and India in IC manufacture, describing the possibility of separating the design from manufacture (silicon foundry approach) where the developing countries would limit their efforts to the design stage.

However, the size and orientation of the domestic market is a key ingredient in any policy analysis of options in IC technology and we will in the final section on policy issues return to this critical area of analysis.

The Republic of Korea experience

There is general agreement that no Asian country other than Japan has provided so much protective nurturing of its electronics industry. The Government of the Republic of Korea and its agencies have, to a considerable extent, borrowed policy approaches from this great neighbour. The original focus was on consumer electronics. The electronics industry in the Republic of Korea has been rapidly progressing both quantitatively and qualitatively as anticipated in the "Electronics Industry Promotion Law" of 1969. Electronics was then explicitly recognized as a strategic export industry with, at the time, less attention given to the domestic market. Advanced technology has also contributed significantly to the industry's growth.

In its initial stages, the electronics industry in the Republic of Korea got its start by assembling radios for domestic consumption in line with the import-substitution development strategy. However, the industry was quickly designated a strategic export industry since, apart from its ability to employ an abundant, highly-skilled labour force, it was technology-intensive. It yielded a high rate of return on investment and also consumed less energy than other industries.

In more recent years the attention has shifted to non consumer electronics products, and in the early 1980s the computer and semiconductor sectors were designated strategic sectors. These sectors were consequently provided with various forms of government protection. Among other hings, an import ban was imposed on personal- and mini-computers. Thus, it was only possible for foreign companies to enter the Korean market by partnership with domestic companies. At the same time a flat rate of 20% import duty was placed on imported integrated circuits. We will now briefly summarize the policies and developments of this sector. I general terms, the policy in the Republic of Korea has three main components: to buy foreign technology; to protect technology latecomers anc to forge joint ventures with leading companies in the USA, western Europe and Japan. The precedent for all these policies can clearly be found in Japan.

Aside from government intervention, the activity is clearly within the private sector where five large companies have taken major initiatives. These companies - Samsung, Gold Star, Hyundai, Korea Electronics and Anam Electric Industries - have all in recent years attempted to establish a foothold in the semiconductor technology.

The IC industry in the Republic of Korea caught up and started to manufacture 256K VLSI memories, which were put in the market by 1985. This was a surprise for the Japanese industry whose own 256K superchip output had earlier shocked the Americans. It is noteworthy that only until 1983, the Koreans were mainly packaging the chips for which most of the things were obtained from abroad.

In the Republic of Korea investment in superchips has been projected at such high level as to make the Japanese competitors take serious note. The R&D project at Samsung Semiconductor and Telecommunication (SST) claims to have begun work on the development of the mask design for its own 256K dynamic random access memory chips using imported wafers. SST's competitor, Gold Star, is reported to be just a few steps behind and is setting up a facility to process 10,000 256K superchips per day. The new business groups, Hyundai and Daewoo, have also entered this field planning to spend US$ 450 million and US$ 290 million respectively, during the period 1984-86. The Government of the Republic of Korea is backing the local industry's involvement in the semiconductor field with financial support of the order of US$ 800 million.[18]

A survey made by the Commercial Section of the US Embassy in Seoul estimates that the five major major makers will invest about US$ 1.7 billion over the years 1985/88 in equipment and production facilities. That is on top of nearly US$ 770 million which are already invested industrywide in plants which are producing mostly products for internal use. Indeed, Daewoo Telecom Co., which due to a money crunch abandoned its infant semiconductor project in 1984, is presently considering reentering the market.

Including government funding, six major firms will invest more than US$ 2 billion in R&D and wafer fabrication facilities by 1988. The common s rategy is to hire Korean-American engineering talent, set up product-design subsidiaries in Silicon Valley to license technology from US companies, and mass-produce the results in the Republic of Korea to take advantage of low labour costs.

Training programs have been established to ensure the supply of highly skilled labour for the VLSI and other projects. During this decade, the country plans to produce 1,360 semiconductor and 820 computer experts. In addition, the Korean Institute of Electronics Technology, conducts basic semiconductor research and then passes along the results to industry.

We will now briefly look into the justification for establishing IC technology in the country.

The Republic of Korea decided that it needed a semi-conductor industry for the following reasons:

* to protect its electronic equipment industry from the effect of any interruption in the supply of chips from the USA or Japan;
* without a semiconductor industry a country can only develop its electronics equipment industry at the same pace as the people who supply the chips decide to develop them;
* to earn foreign currency;
* it was thought that they could be very good at it;
* the Korean electronics equipment industry would become less in price and performance competitive the more it relied on foreign chips;
* at times of chip shortages, as in 1984, the Korean electronics equipment industry suffered due to lack of supply of semiconductors.

USA facilitated Samsung's entry into the semiconductor business, but it was the Japanese, and to a certain extent the British, who motivated it, at least when judging from the anecdotal piece of information. The Japanese motivation came about because they are a dominant trading force in East Asia, yet they have not been keen to let the Republic of Korea gain access to their technology. The British motivation came when Samsung signed a manufacturing deal with Sinclair for the Spectrum and realized that 40% of the cost of the machine is the cost of the semiconductors. The conclusion drawn by the Koreans was that if semiconductors made up so much of the costs of products, and if that proportion was likely to increase rather than decrease, then the domestic Korean electronics equipment industry could hardly be competitive if it relied on imported semiconductors. It was realized that it was better to have own production facilities.

Competitiveness with Japan spurred the Republic of Korea into the semiconductor business because the Japanese semiconductor manufacturers are reported to provide ICs of a special price to their equipment manufacturers. The Koreans also perceived that without a semiconductor industry one cannot develop at own pace. Accordingly, in order to compete with Japan in electronic equipment markets on both cost of manufacture and on performance, an indigenous source of semiconductors was essential. There was only one obstacle. The electronics industry in the Republic of Korea was not big enough to justify the huge investment in chip factories. It was realized from the start that the Korean electronics industry had to be export-oriented.

Simultaneously, Samsung started building plants to produce three device generations - the 64K DRAM in a three-micron production line, the 256K DRAM in a two-micron production, and the Mbit DRAM in a one-micron production line. The factories for the 64K and 256K are both high-volume with 20,000 wafers-a-month facilities at Suwon in the Republic of Korea. The one-micron plant is still a prototype line in Santa Clara, USA, capable of 8,000 wafers-a-month.

Two fundamental weaknesses plague the Korean approach. First, the Republic of Korea is forced to import large amounts of components due to their technology gap with Japan and the USA. The import total has been growing - from US$ 1.69 billion in 1983 to just over US$ 2 billion in 1984, and in 1985 it was estimated to reach US$ 2.3 billion. US and Japanese makers accounted for 84% of the 1984 total, and in 1985 the country was to import an estimated US$ 851 million worth of American components, with Japanese companies selling well over US$ 1.2 billion to the Korean market.

The second weakness is that the Republic of Korea's local market remains small, unlike Japan, which has a well developed domestic market from which to launch its products. The total domestic chip market was in 1984 about US$ 540 million, nearly all of it for inhouse use. A massive infrastructure of telecommunications networks is fuelling growth, but the consumer market for products such as video recorders and color TV sets has been disappointing.

The country's semiconductor industry has been hit by a drop in prices. Critics blame companies for needless risk-taking in their hurry to pour more than US$ 1 billion into R&D. However, the Korea Institute of Economics and Technology (KIET) considers the future the country's semiconductor industry to be bright and it claims that companies will eventually get returns on their investments. According to KIET, semiconductor manufacturing will grow to a US$ 12 billion industry by the year 2000. The share in world semiconductor industry in the Republic of Korea is expected to be 11 %.

The semiconductor industry witnessed dramatic developments in technology during the recent years. In late 1983, Samsung Semiconductor announced the successful local production of a 64K DRAM chip. In early 1984, Samsung again took a major leap in production technology by announcing commercial production of a 256K DRAM chip. Samsung has been less successful, though, on the marketing front. The reason for this was the drop in prices due to Japanese efficiency in manufacturing. The price of 64K DRAM chips fell to 0.40 US cents a piece from more than 1 dollar. Similarly, the price of 256K DRAM chips has also been reduced very rapidly.

In 1985, Goldstar Semiconductor announced the development of a 64K SRAM and a 1 megabit ROM chip. These developments have enhanced the prestige of Korea as the world's third nation to produce a spectrum of state-of-the-art semiconductor devices.

The country's market share in the global semiconductor market is expected to rise from 5.3% in 198[illegible] to 8.8% in 1990. As described earlier, the Republic of Korea relied heavily on imports of a variety of semiconductors until recently. However, in 1984, the country attained a US$ 36 million trade surplus in semiconductors by exporting products valued at US$ 1.19 billion.

KIET predicts that Korean companies will invest 3.07 trillion won in R&D and 4.4 trillion won in new equipment and facilities in the next 15 years. Government support to the industry is nominal with assistance coming only in the form of manpower training and support to private research institutes. Some assistance of R&D is also expected from the National Investment Fund and Electronics Industry Development Fund.

The Indian experience

India is not only a developing country but also a country with a substantial industrial base and technological and scientific infrastructure. Furthermore, the huge population provides potentially very large market for all industrial products, including electronics.

Consequently, it is of considerable interest to understand how India is facing up to the technological challenge in integrated circuits.

Prof Bhattacharyya, Head of the Electronics Research Institute at the Indian Institute of Technology in Delhi, discusses the general incentives for India to venture into VLSI manufacture and some of his arguments are presented below.[19]

The growth rate and total value in production of electronics components in India is much less than that of countries such as the Republic of Korea, Singapore and the Province of Taiwan or even Sri Lanka. This is due to the overpowering demands from other sectors such as steel, agriculture, health etc. In spite of a depressing past record in the electronics component sector, India has, however, decided to enter VLSI enterprise based on the following considerations:

1) The example of some developing countries in allowing multinational companies freely to set up assembly shops is not a viable choice. Two reasons for this are pointed out: (i) labour in India has high individual skill rather than collective productivity and (ii) in a pure assembly operation, real technology flow will not arise and, hence, it is not in the long-term interest of the country.

2) The country is large and has the third largest technical manpower strength in the world. It has acquired fair amount of industrial infrastructure to support an LSI venture.

3) India attaches utmost priority to communication and information processing, which is vital for a country of this size and diversity. If communication has to be revolutionized, there is an optimistic domestic market to sustain a national LSI program.

4) Even if India cannot achieve state-of-the-art LSI technology in the short term, in a large number of industrial sectors where it has its own system-design capability, significant cost-benefit can be accomplished by mere customization rather than by the induction of latest technology.

5) Although in VLSI technology change seems to be the only constant in many systems, the half-life period is relatively long. While for a developed nation, a quick changeover may be necessary for developing countries, the priority of changing the system may not be so desperate. But an in-house domestic capacity is necessary to support spares, etc., to operate the existing system effectively. Such a capability would also ease difficulties here in procuring these vital components which are not industry standard and sometimes single-source dependent.

6) In research a careful strategy of wait and watch should minimize risks in product development.

7) A newcomer, or for that matter, a latecomer in semiconductor technology sometimes stands to benefit from others' mistakes and, hence, has an implicit advantage.

The production of all types of semiconductor devices has increased in India from Rs 235 million in 1979 to Rs. 347 million in 1982 registering a growth rate of about 16%. However, the Indian production of integrated circuits is very small. Production facilities are still on a modest scale. BEL, a major Indian commpany, has set up a production facility for bipolar IC manufacture, mainly SSI/MSI level circuits. However, the consumption of ICs by Indian users has grown rapidly over the past years, thus creating a wide gap between demand and local supply, both in quanity and in types. As regards LSIs, the Department of Electronics has set up a separate unit, namely, Semiconductor Complex Limited, that will cater to the requirements of various users for MOS integrated curcuits. The trial production in this unit was delayed and regular production did not start until 1984. In the area of hybrid circuits, BEL and ITI have got good in-house facilities. In a government report it is noted that somehow, this area has not grown in India, whereas in advanced countries, it has developed a wide range of applications.[20]

At present the maximum demand in terms of number of semiconductor devices comes from consumer electronics, where the requirement is essentially for small-signal diodes and transistors. In 1980-81, all the existing companies (except BEL) have been approved an expansion of then existing 10 to 15 million capacity to 100 million devices per year. However, the pace of implementation has been very sluggish. The expansion of capacity has been largely to meet the requirements of the consumer electronics industry.

In the area of LSI, substantial investments have been made during the Sixth Five Year Plan. There is a need to consolidate this in coming years A demand of 20 million LSIs both for consumer and professional applications is projected for 1989-90.

The same official report mentions that the progress made in the production of SSI/MSI ICs is very tardy and reflects lack of will on the part of manufacturers. Though almost all companies producing small signal devices have been given certain capacity to manufacture ICs, there have been no worthwhile efforts made by anybody with the exception of BEL, which made a half-hearted attempt to meet some of the local demand. High prices of indigeneous ICs, very limited product range, lack of application support to users and poor marketing efforts have been the main reasons for the present state of this industry.

There is one area where a substantial demand already exists and is likely to increase rapidly considering the large expansion in the production of communication equipment, instruments and consumer electronics items. Compared to the production of less than a million devices in 1982-83, a demand of 85 million devices is projected for the year 1989-90. It should be noted that a large part of the new equipment to be taken up for production during the Seventh Plan in defence and communication area, will be based on SSI/MSI devices.

In the report of the study team on components and materials it is claimed that the current gap in LSI/VLSI technology between India and the advanced countries is estimated at approximately 15 years. With the initiation of trial production in Semiconductor Complex Ltd (SCL), the existing production capability in India has been augmented to 5 micro feature size. Production capability of 1.25 micron level has already been achieved by 1985 in advanced countries and it is expected to further reduce to 0.5 micron by 1990.

The Task Force on LSI/VLSI has drawn up a comprehensive programme over a very broad spectrum in order to upgrade the total technological base in India in the area of ICs, various infrastructure and input technologies needed for their manufacture and to develop and upgrade the existing manpower base.

Technology Goals

The Task Force has set up the following technology goals:
(i) 2 micro CMOS & NMOS silicon gate and bipolar technologies developed to R&D level by 1988 and production level by 1990.
(ii) 1.25 micron technology at R&D/pilot line stage by 1990.

The intermediate goal has been to achieve 3 micron capability by 1985.

Strategy for Development

IC Technology

Development of IC technology will mainly involve the following:
(i) Understanding of the device behaviour as smaller geometries are used in effecting suitable modification in the device structure to ensure desired functional operations. Also new structures/processes will have to be developed for improved production and products with special performance characteristics.
(ii) Development of unit processes to achieve the device structure as defined above.
(ii) Process modelling.

Furthermore, the Task Force has made an analysis of the cost of production of LSI devices and found that about 50% of the cost is accounted for materials which are being imported. It has thus set a goal of meeting at least half of the country's requirements of such materials in terms of value from local sources by 1990. This would require intensive R&D efforts and the establishment of a proper production base.

The Electronics Commission has recently accepted a recommendation by the Task Force in 1982, and a decision was taken to set up a National Microelectronic Council (NMC). This council (15 members) will act as the central body to formulate, implement and regulate the short and long-term national strategies in the microelectronics sector. Coming in the wake of the controversy over the American technology that has been contracted for the national silicon facility in Baroda, the formation of this council would seem as an emergency step to resolve the issue. The report of the Task Force envisages a programme, with an outlay of Rs 400 crores, to develop a national capability of fabricating one million components on a microchip based on 1-micron technology from the level of 33,000 components on a chip based on 5-micron technology over a decade. The technology that was available in the country through the national semiconductor complex, Chandigarh, was based on 5-micron semi-custom design technology, bought from American Microelectronics Incorporated. This existing technology suffices to generate some coder-decoder and micro-processor circuit designs in the large-scale integrated area.

The NMC, which has full executive and financial powers, will periodically review and update R&D, production and applications in the field of microelectronics. It will take measures to bring about maximum standardization to meet the national requirement of microelectronic systems. The council will further take measures to ensure that specific user requirements, particularly in critical and strategic areas, will be formulated. A comprehensive plan to generate in the shortest possible time, in order to utilise properly the scientific and technical manpower, will be drawn up by the council. It has also the responsibility of formulating fiscal, import and industrial licensing policies for the microelectronics sector.[21]

A fundamental shortcoming for establishing an IC manufacturing capability in India has been the limited size of the market. It has been calculated that in 1981-82 the LSI content of total electronics production in India amounted to Rs. 36.6 million.[22] This market was divided between the various electronics subsectors in the following way:

1. Consumer electronics	Rs 10.0 million
2. Telecommunications systems	Rs 7.0 million
3. Computers	Rs 13.0 million
4. Space	Rs 4.6 million
5. Defence	Rs 2.0 million

Source: Electronics, Information and Planning, January 1984, p. 194. Presented in C. Edquist & S. Jacobsson; The integrated circuit industries of India and the Republic of Korea. RPI, 1985. (Mimeo) To be published in Industry and Development early autumn, 1986.

In 1981-82 there was no production of LSI in India, but the total value of production of SSI and MSI amounted to approximately Rs 20 million. Edquist & Jacobsson note that it would appear as if the annual total market has increased considerably since then. In early 1985 Mehta suggested tha the annual market was US$ 15-19 million or around Rs 14 million. Out of these, however, US$ 5-7 million were in the form of custom desinged ICs. The authors also state that it should be noted that the local prices were higher than the international ones, thus inflating the size of the Indian market. Prof. Bhattacharyya presents the following arguments:[23]

First, he states that for the viability of a VLSI venture in any country, the availability of an internal or external market becomes a vital consideration. For 1990, an ad hoc figure of production capacity worth US$ 60 billion is assumed in the USA, US$ 20 billion in Japan, US$ 4 billion in western Europe, and US$ 1 billion in the rest of the world (excluding the USSR). With its existing organizations, India has a projected production capacity of US$ 100 million. At the present level the electronics production output in India is less than 1% of GNP against 5-7% in advanced countries. With modernization, therefore, there is naturally a projection of an optimistic demand figure.

A conservative estimate predicts that the demand for indigenously produced LSIs with the present level of use of only 1% LSI chips in the system, will reach the worth of US$ 100 million by 1990. It is believed that within a decade an advanced system design should contain about 20% LSI chips. Assuming that our learning curve enables us to use a modest 10% LSI chips, the market for indigeneous LSI chips should increase to US$ 500 million. The above target excludes defense requirements. At the present level, India has no export in LSIs, and overtaking the USA, Japan, or western Europe in any area seems improbable.

THE DEVELOPMENT OF THE IC INDUSTRY IN DEVELOPING COUNTRIES[24]

The earlier discussion of the experiences of the Republic of Korea and India have clearly shown that an advanced newly industrialized country (NIC) must overcome tremendous hurdles in order to establish a real foothold in IC technology. Thus, it is natural for most developing countries to look more carefully for alternative policy options. In this context, the possibility of separating design from manufacture merits serious consideration.

There are many reasons for fostering and promoting design activities for integrated circuits in developing countries. Since the chips used for certain applications are primarily needed in the developing countries, the motivation for those specific designs could naturally be stronger in these countries. Furthermore, and even more important, the possibility of designing customized chips for such applications could itself act as an incentive to the rapid absorption and deployment of the microelectronics technology for development-catalyzing applications. A well developed design base could act as a focus for creative activity in high-quality science and technology. This design activity could generate interest and engagement in related fields, e.g. graphics, CAD, software engineering etc. In certain cases this could even trigger off interest and activity in hardware design and construction thus assisting the design activity of microelectronics chips.

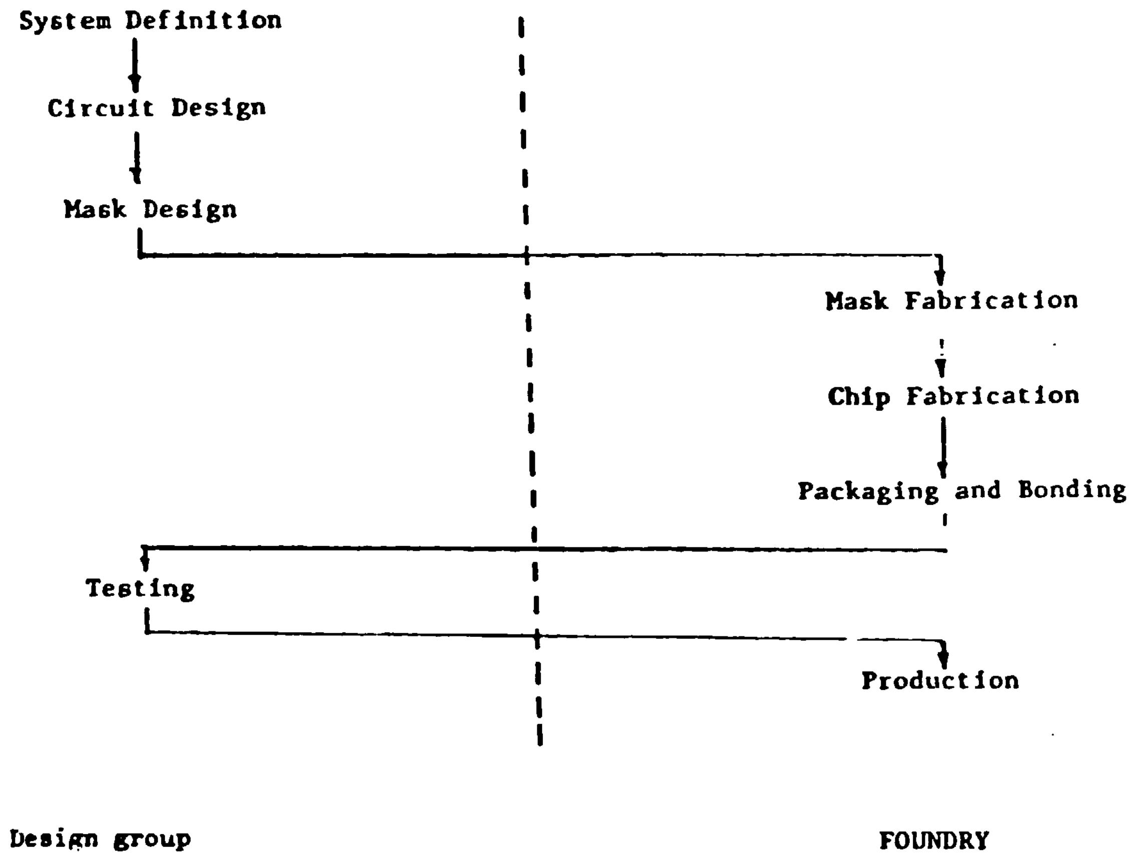
One major characteristic of the integrated circuit industry in the past has been its vertical integration, at least to the stage of circuit production. The process of turning an idea into ready integrated circuits includes many steps. The initial steps of system definition, logic design, circuit design and mask design are manpower intensive and require a large amount of "thinking power". Therefore those steps depend upon having a set of design skills which are almost independent of how the device will actually be made. These steps also establish the eventual function of the device. On the other hand, the steps including mask fabrication, chip fabrication, bonding and packaging require technical skills as well as sophisticated equipment and appropriate facilities (see Figure III). Once the fabrication process has been properly established no changes are required in order to produce completely different integrated circuits (see Figure IV). Nonetheless, since the capital cost required for such fabrication as well as the operating costs for these activities are very high, it is only very few large companies which can afford taking the risk of establishing a fabrication line.

Figure III
Traditional microcircuit design steps

System Definition
↓
Circuit Design
↓
Mask Design
↓
Mask Fabrication
↓
Chip Fabrication
↓
Packaging and Bonding
↓
Testing
↓
Production

Figure IV

Silicon foundry approach to custom integrated circuit design



Source: A silicon foundry to service developing countries' needs: a preliminary approach. UNIDO/IS.444. Vienna 1984.

Facility investment trends for the establishment of a production module for fabrication of IC wafers rise sharply with shrinking feature size. A typical module investment of a self-contained operation designed for a single process technology of 2-micron capability and handling 1500 wafer starts per day, is approximately $60 million. Even if some parameters are reduced, the investment costs would not be less than $30 million. This expense is often out of reach for most developing countries, partly due to the problems associated with marketing the complex technology.

There is a fixed minimum cost which is associated with the manufacture of the set of masks required for the fabrication and production run of one batch of wafers. This cost is presently in the area of $30,000. A single batch of wafers produces several thousand identical circuits and therefore the cost per circuit is low. However, circuit design always includes at least one prototype run to demonstrate the successful operation of the new circuit. The cost of a minimum wafer run is the same for both a prototype circuit or a proven design. Furthermore, several prototype runs are often required before the design is completely satisfactory, and this makes development costs very high. The real difficulty with prototyping is that using the normal procedures one still gets several thousand chips from a minimum run even though only a few are really required for testing purposes.

Several recent innovations have changed this situation dramatically. One of these is the so-called multiproject chip. Each chip on the wafer contains between five and ten independent prototype designs. During the bonding and packaging steps only one circuit on each chip is actually connected to the pins on the package. All other circuits are dormant. However, enough samples of each circuit have to be produced from a single wafer run in order to ensure adequate testing. The cost of the prototype production can be shared by a number of different designers. Nevertheless, even with multiproject chips many more samples are produced than what is actually required. The obvious next step is to produce a set of masks which have many different chip designs on them. Each chip design can still be a multiproject chip. This results in what is called a multiproject wafer. Thirty or forty independent prototype circuits can be produced from one fabrication run and the cost shared.

Based on the same principle of sharing costs, different steps in the fabrication process could be distributed and performed in various countries. Separating production facilities from the location of the design activities could lead to reduced entry costs for each country. Moreover, national design groups could prepare the designs of chips specifically needed in their own countries, and the skills acquired by members of these groups in the common development efforts could influence the countries' technological development.

One of the initial tasks facing a designer of custom circuits is designing the subcircuits - such as gates and registers - which will be combined and used many times to produce the final design. Several commercial companies supply already a library of tested standard cells for a variety of different fabrication processes. The designer then has only to select, place and interconnect these standard cells in order to produce a prototype custom design. Since design time is reduced, development costs are also cut down. Furthermore, since most of the circuit design is incorporated in the library of standard cells, the design skills required are limited mainly to system design.

Even though the design of LSI/VLSI chips could be undertaken by the developing countries to meet special application demands, the stage of converting these designs into actual hardware - i.e. fabrication - may be beyond the means of most developing countries. However, if the developing countries follow the silicon foundry approach and pull their resources together, then a fabrication facility could be established as a joint enterprise.

There may exist a clear case for establishing a silicon foundry for joint use by developing countries to meet their fabrication needs. The foundry must trough, be a base not only for fabrication, but also for providing training and transferring design know-how. The establishment should thus have high capacity in all the design and fabrication stages of circuit production. However, the design and training activities could also be carried out independently in national design focal points in many different countries. It is only fabrication that should be located in one place.

An important issue in this context is the type of technology to be catered by such a foundry. Principally, it has to meet two criteria. First, the technology must be operationally well understood and it should be readily established. Second, the foundry should be able to process wafers of a degree of complexity which accomodates the kinds of application needs required by the different designers. Both these considerations would suggest MOS technology capable of handling a 2-micron geometry. LSIs and the initial end of VLSIs could be handled by such a foundary immediately. This should serve the needs of the developing countries during the 1980s. While using this installed technology during the coming decade, the foundary could equip itself to meet demands involving the next level of sophistication in the 1990s.

We will now provide a few additional comments on the development of the microelectronics industry in three Asian countries - the Republic of Korea, Malaysia and Singapore. These three countries have been major exporters of integrated circuits - Malaysia is reported to be the world's leading exporter of ICs used in computers and other electronic equipment, followed by the Republic of Korea and Singapore.[25] The Republic of Korea, though, should be placed in a category of its own due to its ambitious and advanced plans of establishing an international bridgehead in IC-technology.

Most of the manufacture in Singapore and Malaysia has been labour-intensive assembly in the downstream processes with the advanced wafer-manufacture taking place in the US, Europe or Japan. For example, in 1983, the Republic of Korea produced 670 million dollars worth of integrated circuits mostly for Japanese and US manufacturers on a subcontract basis.[26] According to one source, Malaysian production of semiconductors and ICs in 1984 is estimated to amount to US$ 2.4 bn.[27] Another source reports that Malaysia currently assembles and exports around $1.5 bn worth of semiconductors, principally through the subsidiaries of American and Japanese companies.[28]

Singapore and Malaysia are recently facing a completely new situation in which the multinationals are withdrawing their assembly operations and consolidating the production process in their home countries or in a limited number of places.

This has prompted Malaysia to strengthen its own position in the microelectronics sector. One of the actions taken for this purpose is the recent establishment of the Malaysian Institute of Microelectonics Systems (MIMOS). This is a government body set up to design microchips for specific new applications and it will offer its designs to commercial enterprises for production. MIMOS planned to set up a commercial integrated design centre before the end of 1985 with the aim to diversify away from assembly into circuit designs and VLSI circuits. However, since Malaysia's only experience of the microelectronics industry is the assembly of ICs, MIMOS's first priority is the training of local personnel. The main areas for further research will be computer systems, CAD, information technology and industrial applications.[29]

It is noteworthy that several of the participants in the Malaysian project are multinational telecommunication corporations which are eager to remain in the local market. Thus, it appears that the developing countries have a leverage in the access to their own market and telecommunications is in many, or in most developing countries, a market which is likely to rapidly expand and at the same time become increasingly electronic in nature.

Also Singapore has realized the need to make more efforts to uphold market shares for its microelectronics industry. The overall government policy aims to make Singapore the "silicon valley" of the Pacific Basin. One alternative considered is to specialize in semi-custom and full custom design of integrated circuits. All new strategies will however demand a large investment in equipment and training.

TECHNOLOGY CHALLENGES FOR DEVELOPING COUNTRIES

The earlier sections of this paper have shown that the electronics industry is one of the fastest growing industrial sectors. Integrated circuits is not only a very important part of the electronics industry, but also an integral part of this sector. Although it constitutes only around 5% of the production value of the electronics sector its importance is continuously increasing as the functions provided by the ICs are made available at lower costs. The major factor responsible for this is the rapid technological development, not only of the circuits, but also within the manufacturing process which has now increasingly come to be dominated by the equipment manufacturers.

This development might lead to a situation where only a limited number of global companies will be able to remain in the highly competitive market for high volume integrated circuits. The technological capability in semiconductor technology of all major industrialized countries has been shown to be important for future industrial development all over the world. Governments in several countries have allocated considerable resources to the support and further development of the domestic IC industry. Integrated circuits are often referred to as the "oil of industry", or as in Japan the "rice of industry". However, the rapidness of technological change combined with the high investment costs for up to date production facilities have proven to be a very effective barrier for most countries to enter into the market. It is only India and China among the developing countries as well as some NICs, which have seriously considered to develop a major capability in IC manufacture.

The manufacture of integrated circuits includes five major processes - circuit design, maskmaking, wafer production, assembly (packaging) and testing. The rapid development of application specific integrated circuits (ASIC) has changed the possibilities for entering the first stage. Tremendously powerful computer technology has proved to be very useful in the computer assisted design (CAD) equipment which is now available to the circuit designers. It is, in fact, possible to talk about a democratization of technology as far as the first stage of IC manufacture. In recent years this sector appears to have been increasingly dominated by a small number of larger companies. It is still uncertain whether this is a temporary phenomenon in the development of IC technology. There can be no doubt, however, that the mainstream IC technologies will continue to be developed and controlled by a small number of large companies. It is therefore far from certain that the "democratization" of the design stage will actually change the overall structure of global IC manufacture. The major hindrance may be the technological changes in the manufacturing process itself. The future lev-ls of integration require, or rather are made possible by, among other things, the reduction of line-widths. This requires, in turn production processes which in complexity and costs will, in all likelihood, seriously limit the number of manufacturers of advanced IC circuits. However, the options will be broader if both the makers and users of ASICs will be satisfied with considerable larger line-widths than what is used in the most advanced ICs.

There can be no doubt that the manufacture of electronics products and the use of such products will become increasingly important in all countries and developing countries are no exception. However, the level of economic, technological and industrial development, which is partly a reflection of size, and the market will be of importance for the decision upon the policy options which are available to a country. The market consists both of the domestic and export markets but for most developing countries export is of relatively minor importance when it comes to electronics products. We will now try to explain the limitations and possibilities for various categories of developing countries. Please refer to Table 7 below.

The major issue is the degree of complexity of the electronic product. The use of professional equipment is at the lower end of the spectrum. In many developing countries, the actual use may be severely constrained by the lack of relevant skills, both at the operational level and for maintenance. We refer to developing countries at the early stages of development. The next level of complexity is the manufacture of most types of electronic products - most typically exemplified by consumer electronics. Such production is ruled out for most developing countries unless it is carried in collaboration with a counterpart in an industrialized country. For several of the newly developed industrialized countries (NICs) an independent manufacturing capability is in the main limited to consumer electronics. A third level of complexity is exemplified by the manufacture of semiconductor components. With the exception of the Republic of Korea in the group of NICs and India and China, among the developing countries, there exists no independnet capability except for the case of relatively simple semiconductor devices. However, the two industrialized developing countries - China and India - are in the process of establishing an independent capability for an intermediate range of advanced semiconductor devices.

Table 7
The significance of technological complexity and constraints on domestic capabilities in the electronics sector

	Complexity of manufacturing operations			
	-----Capital Goods---	---Electronics Industry-----------		
"Stage of national development"	Use of professional electronic equipment	Manufacture of electronic equipment	Manufacture of semiconductor components	Manufacture of complex electronic systems
Developing countries at the early stages of development	severely constrained	generally not possible	impossible	impossible
Developing countries	possible with certain constraints	only possible through collaboration	not possible	not possible
Newly industrialized countries (NICs)	without constraints	possible but in the main limited to consumer electronics	independent possibility impossible for the time being	only possible through collaboration
Industrialized developing countries (India & China)	without constraints	general capability possible	independent capability constrained and at high costs	independent capability severely constrained and at high costs
Industrialized countries (e.g. Sweden, USA)	without constraints	general capability possible but economies of scale requires specialization	general capability only possible for a few countries	possible only for a few big countries or smaller ones with viable international companies

In many respects, the industrial strategies and available resources in India and China resemble more those of industrialized countries than those of the NICs. However, when it comes to the manufacture of complex electronic systems like modern telecommunications equipment, even these two countries are todey severly constrained and the reasons are twofold. First, the domestic markets in these two countries do not yet justify the allocation of development resources which are required to establish a domestic frontline technological capability. Second, the agencies concerned may only at a relatively late date have become aware of the character of the very rapid technological change which is affecting electronics systems due to the rapid changes in semiconductor technology.

These comments on the capability in developing countries do in no way indicate that industrialized countries have a general capability to engage in whatever level of complexity of manufacturing operations. All industrial countries, with the possible exception of the US and Japan, are seriously constrained by the size of their domestic markets as many categories of electronic products must be based on substantial economies of scale. This is certainly true for modern telecommunications sytems and it is one of the major reasons for the dominance of a limited number of multinational companies in this sector which are all based in the industrialized countries.

What options are open to the developing countries? The majority of them have limited bargaining power and a narrow industrial and technological base to establish domestic manufacture of electronics products. This group of countries will have to buy the products from outside unless they can attract production facilities considering the domestic and regional markets. A small number of countries, notably the NICs, have a technological base and access to sufficiently large markets, domestically and/or for export, in order to enable them to enter into negotiations with major international partners. Such a strong bargaining postion, possibly even stronger, is also available to India and China.

The question then arises of the conditions set by the companies with the most advanced technology, be they multinational companies or smaller ones, for handing their technological assets. In every deal the seller is being partly paid for development costs which in fact means sharing technology costs but not getting access to the next generation technology unless one pays a second installment. This may mean that the multinational companies may be able to maintain their oligopoly and force the developing countries to share the development costs as long as the technological change continues at the present high speed.

Changes in the semiconductor industry over the past couple of years may, in fact, mean a reversal of the constraint levels for electronic products. Thus, due to technological change and required scale of operation, the highest barrier of entry is today found in the manufacture of IC circuits.

Before discussing the policy options in application specific integrated circuits (ASICs) it is necesary to realize that there will not be any demand for ASICs unless there is a domestic industry requiring such circuits. Such a domestic electronics industry will not come through unless there is a domestic market for electronics systems and/or specialized electronics products. A foreign manufacturer basing itself in a developing country for the purpose of exporting will in all likelihood not provide a market for local manfuacture of ASICs. Thus, we are discussing countries which today have an already established basis in the production of electronics systems, or that are in the process of establishing such a capability.

The major justification for companies in advanced industrialized countries has been a desire, or a need, to optimize design parameters and reduce costs in order to stay competitive. The same factors may be less important in a developing country, although they may apply in a NIC which has its industry geared towards exports. However, a developing country in the process of supporting a budding industry in electronics system is likely to produce at low scale of manufacture and at the same time attempt to adjust system products to local conditions. Such a situation would warrant the use of application specific integrated circuits.

There are the following requirements for successfully establishing a competence in ASICs. First, the earlier discussion has revealed the need for an advanced capability in system designs which follows logically from the earlier requirement. Second, an already established or ability to establish a close relationsship with the manufacturer of integrated circuirts is required. Only a limited number of developing country have such a capability. On the assumption that line widths for the monolithic semi-custom ICs will be much thicker that for frontline ICs, is it realistic to establish

a silicon facility in the country. In most cases this would not be considered. (An issue to be furtherly discussed)

There are a few additional requirements to be met. First, the country needs a sufficient number of competent system engineers who can design the circuits. Second, the system engineers must have at their disposal advanced desigr facilities such as computer aided design (CAD) , libraries for IC cells and routing pattern, and simulation programs for testing, etc.

The discussion in this section indicates that only a limited number of developing countries are in the position to independently establish their capability in application specific integrated circuits. At least initially, most developing countries would have to enter into a partnership with a foreign company.

Another possibility is to establish regional co-operation. In this case the design of integrated circuits could be established independently on a national level in design centres of many different countries, whereas fabrication should preferably have only one location inside (or initially even outside) the region.

The idea of separation of production facilities located in one selected place from the design, which could be distributed and performed in many different countries, decreases the entry cost for each country. Besides that, national design groups could prepare the designs of chips specifically needed in their countries. The skills acquired by members of these groups could influence the countries' technological development.

POLICY ISSUES

There is presently almost a concensus that it is impossible to remain outside the realm of new technologies and this has been exemplified by electronics. Naturally, there are many options for a developing country, but the major task facing them all will be to achieve a changeover to VLSI in all the existing electronics sectors - communication, control, transportation, medicine, defence etc - sooner rather than later, if such systems are intended to be anywhere near up to date. Prof Bhattacharyya[30] argues that there will be three possible routes for this transformation: (a) A revolution strategy where immediate updating and modernization of all the electronics systems are envisaged. This is rather an unlikely step in most countries because of the enormous pressure on funds, manpower, training, etc.. (b) An inert strategy of waiting till an electronics system has completely outlived its utility and then replace it by systems based on VLSI. (c) An evolution strategy which is a mean path between (a) and (b) and which calls for updating the system that will meet present and future requirements and at the same time remains compatible with the present environment.

In the article referred to earlier, Bhattacharyya discusses the different options.[31] But first he highlights the characteristics of the VLSI revolution. The transition to the new VLSI era is experienced by many industrialized countries as a rather painful process. Thus, it is obvious that the developing countries find themselves outpaced. It is unfortunate that VLSI technology - the future technology for social and economic transformation - is based on a technological level of sophistication that is beyond the immediate reach of most developing countries.

There is no doubt that our civilization will be dominated by microelectronics in the future. While the developed world will be able to utilize the new opportunity for the creation of their world, the priorities and perspectives for the developing countries are different. The industrialized countries can use VLSI for achieving their goals of national satisfaction, intellectual creation and self-realization - leaving labour to machines. The developing countries must, according to Bhattacharyya, respond to the challenge of VLSI with two prime motivations: (i) a technology is a vehicle for quick social transformation and hence cannot be ignored, and (ii) it has been learnt from history that technology can be synonymous with freedom.

Bhattacharyya sees the following options for the development of VLSI technology.

A. Indigeneous R&D: This is perhaps the dream of all developing countries, if circumstances permit.

B. Technology importation: Direct importation of VLSI technology may be considered a viable alternative by many developing countries.

C. Multinational enterprise: Some developing countries may prefer to invite multinational enterprises to set up their VLSI technology - fully or in part - in the respective countries.

D. Joint venture: One of the reasons for established industries to attempt joint ventures is to make use of the research base of the host country in view of either their skill clusters or economy. An open question, however, is whether a partnership with a developing country which has a weak base in science and technology would be of any attraction. The infrastructural and political considerations will be the key factors for developing countries when deciding their course of action. Many countries hold the view that the most prudent for developing nations is to adopt the latest available technology and absorb it.

Bhattacharyya emphasizes that the development of VLSI technology revolves round a wide base of science and technology. Therefore, developing countries set for the domestic development of VLSI should take note of such involvements as a wide range of process and technology development, modeling, CAD, analysis and testing, metallurgy for package development, automated optical and electron-optical equipments, software for application, operation systems and languages, quality control and failure analysis etc.

This covers almost the whole range of scientific and technological activity requiring a strong base. Further, if the experience of European countries is any indication, even a strong scientific base will hardly render VLSI economically effective, or even sustainable, in developing countries. VLSI will play, however, an effective role in developing countries in information processing, where software development assumes considerable importance. It is human skill intensive and thus more adaptable to developing countries.

Bhattacharyya is of the opinion that - in contrary to the general belief that technology, equipment or resources are the biggest hurdle in LSI development - the manpower shortage could be the single factor inhibiting the planning and launching of the VLSI era in developing countries. However, the experience of many countries indicates that the size of the market, the rate of growth and the linkages within the industrial structure are even more important in this context. We will return to these issues later on.

Another issue to be considered is the overall cost for entering into a new technological field. This is an issue closely related to that of market size and rate of market increase.

Entering a new technological/industrial field involves considerable costs and available evidence indicates that the entrance fee for many fields is rapidly increasing. In order to understand the role of entrance fee and in order to be able to analyze the situation, it is necessary to make a distinction between different cost categories which require the paying of an entrance fee. The main categories are (1) Costs associated with production plant or processes in production. This is exemplified by the manufacture of VLSI. (2) Costs required for development, including research necessary for establishing the knowledge base for a prototype or a new product. This is exemplified by robot prototypes or the pharmaceutical industry.

The intrinsic nature of technology - its complexity and increasing interrelationship as well as external demands - clearly indicates that the above mentioned figures, in real terms, continue increasing. Thus it becomes more difficult to enter into various newly emerging industrial fields. In fact, the entrance fee is becoming so high that the potential entrants are becoming quite limited in number.

Concluding Remarks

This document does not provide any simple answer on how a developing country should be reaping the benefits of IC technology - now almost completely controlled by a limited number of companies in the industrialized countries. However, three facts are almost beyond question. First, the IC technology has become a pervasive technology which affects all industry and almost all aspects of society. Second, the complexity of the technology and associated economies of scale, both in the research phase and in the production stage, have created a very considerable financial, technological and managerial barrier which few countries and companies appear to be able to climb today. Third, the very rapid technological change - fuelled by intensive competition among nations and companies in the industrialized countries - is likely to continue for a decade or more.

Given such a situation the developing countries must - in all likelihood - reassess their situation and view the research and production stages of the semiconductor industry as similar to development and manufacture of commercial aircraft and spacecraft. Thus only a few of the biggest developing countries can potentially enter the league of the industrialized countries with their advanced companies.

However, most developing countries are not excluded from using advanced aircraft in commercial international airlines. Is it a natural analogy to view the R&D and production structure for the semiconductor industry as similar to that advanced aircraft?

If that is a relevant analogy most developing countries - and several industrialized countries - should be more concerned with the applications of IC technology than the production capability for semiconductors. Such possibilities may be enhanced by rapid advances of application specific integrated circuits (ASICs) described in this paper. However, it is not yet obvious to what extent the design phase can be separated from production of ICs considering the very high rate of development of IC manufacturing technology. This issue requires further study.

The many related issues must be studied in considerable detail and the present document has only superficially indicated some of the issues. The actual and potential demand for IC technology and how the domestic demand structure can be influenced and exploited is one of the critical issues which must be studied.

Notes

(1) Dataquest as quoted in Science and Technology Brief, The Economist, December 8, 1984, p.93.

(2) Meindl, J.D.: Theoretical, practical and analytical limits in ULSI. IEDM, No 9, 1983.

(3) Robinson, Arthur L.: One billion transistors on a chip. Science, January 20, 1984.

(4) Bottoms, Wilmer R.: Equipment requirements for submicron VLSI production. Solid State Technology, August 1984.

(5) The discussion on automation to follow is based on Hutcheson, Dan: Economics in wafer processing automation. Semiconductor International, January 1985.

(6) Uttal, Bro: Who will survive the microchip shakeout. Fortune, January 6, 1986.

(7) Excerpted from Handbook of components for electronics, edited by Charles A. Harber, New York: McGraw Hill, 1977.

(8) Science and Technology Brief, The Economist, December 8, 1984, p. 93.

(9) Penn, M.G.: Impact and opportunities for application specific integration circuits (ASICs). IEE Proceedings, Vol. 132, Pts E and I, No 2, March/April 1985.

(10) Penn says that from a technology point of view, CMOS is expected to become the dominant technology; more specifically, a sub-2 um, double layer metal, CMOS silicon gate technology will predominate. Bipolar processing will be used exclusively for either very fast systems, for example, sub-1 ns gate delay ECL systems, or applications which can invoke fully integrated 'systems-on-a-chip' solutions, and where a substantial degree of nondigital functions and interface to high-power devices is required.

(11) Stansberry, Mark C.: Gate array design. A hierarchical development trend, Electronics + Power, July 1985, p.519.

(12) The following comments have been excerpted from Watts, Andrew: The CAE workstation in semi-custom design. Electronics + Power, July 1985, p. 523.

(13) This includes complex graphic macro entry and circuit verification, including logic simulation, timing and test development combined with the automated tools of conventional full-custom IC layout, full utilization of the workstation's accelerator being carried out for the computationally intensive tasks.

(14) Arnold, J.S.: Trends in the application of semiconductor technology. IEE Proceedings, Vol. 132, Pts E and I, No 2, March/April 1985.

(15) It is also argued by Arnold that the parametric cell is a convenient way to include regular arrays in components. In addition, there is the capability to specify a subcircuit formed from a group of cells as a macrocell which can be repeated on a chip, used to create an array, or held for re-use in another design. Larger cells such as 4, 8 and 16 bit microprocessors are likely to be available in the near future. There are also two advantages in including a parametric gate array in the library. First, it will allow changes to be introduced at the metal level, for example for a range of similar devices. Secondly, by placing all the random logic on a chip within the bounds of one or more gate array cells, and using the autorouter to make the connections within each gate array Paracell, a routing hierarchy is obtained which greatly simplifies the routing problems and reduces overall design and computer time. Alternatives to standard cell design procedure have been developed.

(16) Totton, K.A.E.: Review of built-in test methodologies for gate arrays. IEE Proceedings, Vol 132, Pts E and I. No 2, March/April 1985. Also, Turino, Jon: Coming major changes in test. The vendors seem to be approaching the real needs of ATE users. Semiconductor International, January 1985.

(17) The traditional approach has been to utilize the design verification stimulus as an input to a fault simulator and to add extra tests to detect outstanding faults.

(18) ELCINA Delegation visit to the Far East - A report. Electronics, Information and Planning, Vol 12, No 7, April 1985, pp 425-448.

(19) Bhattacharayya, A.B.: VLSI - The technological giant - and the developing countries. Proceedings of the IEEE, Vol 71, No 1, January 1983, pp 144-148.

(20) This situation may be rather typical for most developing countries - even major ones like India. There is a considerable amount of official information available on the Indian situation. The most important source for this material is Electronics, Information and Planning.

(21) The Hindu, 16 February 1985.

(22) Electronics, Information and Planning, January 1984, p. 194. Quoted in Edquist C. and Jacobsson S.: The integrated circuit industries of India and the Republic of Korea in an international technoeconomic context. Mimeo, Lund: RPI 1985. To be published in Industry and Development early autumn 1986.

(23) Same as note 19.

(24) The discussion in this section on information obtained in A silicon foundry to service developing countries' needs: a preliminary approach. Report prepared by the UNIDO Secretariat. UNIDO/IS.444, Vienna 1984.

(25) T, 23 April 1985, p. 24; STBT, 23 March 1985, p. 4, STBT, 15 May 1985, p. 1.

(26) JIJI, 14 October 1985.

(27) STBT, 23 March 1985, p. 4.

(28) IHT, 7 March 1985, p. 13.

(29) MALB, 1 August 1985, p. 68; BTMAL, 24 May 1985, p. 1.

(30) Batthacharyya, A.T. See note 19.

(31) Same as note 30.

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PROCEDURES FOR RETRIEVAL OF BIBLIOGRAPHIC MATERIAL

Two international online databases have been primarily identified as most relevant for this study: INSPEC and COMPENDEX.

INSPEC (Information Services for the Physics and Engineering Communities) online database is one of the largest files in the physico-technical domain. The database was started in 1969 and contains presently nearly 2.5 million records published in the areas of computing, control, electrical engineering, electronics, physics and information technology. The current annual growth of the file is of more than 200.000 records.

COMPENDEX (Computerized Engineering Index) covers literature in the fields of engineering and technology as well as biotechnology. This database was started in 1969 and contains presently nearly 1.5 million records. The file increases about 90.000 references a year.

Both databases mentioned above are accessible via ESA-QUEST system. The ESA Information Restrieval Service is a database host organization forming part of the European Space Agency. There are 11 member countries participating in this programme and headquarters are located in Frescati, Italy. The network contains over 105 files including both bibliographic, fact and patent databases.

With the equipment available to us we have been able to get access to ESA either through DATAPAK (directly via the Swedish telecommunications system) or through SUNET lines.

This latter alternative can be used with direct computer connection to the university's computer center, but since the location of the Research Policy Institute lies outside the network area, we had to use a modem for communication.

A tentative online search was set up in November 1985 in order to get acquainted with the ESA network and the QUEST language system. The descriptions used for items identification were the following: "semiconductor", "integrated circuits", "gate arrays", "semicustom", "technological trend" and "economics". Several abbreviations were aslo used: "IC", "ASIC", "VLSI". In order to get an overview of related terms, a text analysis was done with respect to words' frequency.

The resulting references were printed out on line in a format including all bibliographic information as well as abstracts.

In January 1986, a somewhat modified search with more precise descriptions was carried out in both INSPEC and COMPENDEX. Again, ESA-QUEST was used as database host system.

Keywords were identified by Jon Sigurdson, and Yael Taagerud elaborated these with help of the INSPEC thesaurus. This volume is of great help when constructing a search profile since it has very good cross references to related/broader/narrower terms. Since the primary result of the search, based only on keywords, was too large, we limited it to the years 1984-85. This was done on the assumption that the technologies of interest undergo continuous development, and therefore recent articles are most relevant when analysing technological forecasting and economic trends. This was also the reason why we mainly concentrated on journal articles and conference papers rather than books.

The results of these searches were printed out in a format including bibliographic data. The searches were then saved in the network so that we would be able to return to them later on. After a review of the titles, we selected a number of references, and printed them in a format including an abstract. (This was made possible by re-entering the saved searches).

Several articles were selected for full retrieval and we obtained most of them from the University Library in Lund. Since the journal collection covers many of the issues of interest to us, we found more material of relevance while looking for these articles.

Another useful source of information was a standing search profile which we had at the Royal Institute of Technology in Stockholm. The Information and Documentation Center (IDC) of this Institute has established an Information Retrieval service for subscribers who wish to obtain continuous coverage of entries in ESA files. The profile is processed every two weeks, when IDC receives the records from ESA. This service, called EPOS/VIRA is unique in Scandinavia.

The journals which were not available in Lund were located with help of the LIBRIS computer system, which is a Swedish database for literature included in all University libraries and many research/industry libraries. Thus, we could, for example, obtain very important material from the library of the Swedish Defence Research Agency in Linkoping.

The articles herewith obtained together with material acquired earlier on by the authors, constituted the frame for this paper. When looking into issues related to new advanced technologies, there are always plenty of technical descriptions of the latest developments. These aspects could not be overlooked and therefore we even took into consideration short articles/notices in the various electronics journals.

Those journals included also articles of an overview nature which the authors of this report could then compile with the in order to create the ground for a policy-oriented study. Electronics Week (or Electronics as it has changed title several times during the past years), has a good coverage of general issues related to the semiconductor industry. It presents an annual economic perspective in a series of special reports which showed to be very useful.

Another important source was the journal Solid State Technology. Here we found several articles covering many aspects of the technological trends. IEE Proceedings is also of great value in this respect. Articles analysing different economic aspects of the latest developments are also published in Semiconductor International. Many references were also made to VLSI Design which is also an eminent journal on certain issues of this report.

For the definitions of terms we also turned to various handbooks and books. The authors have compiled the present material with the hope to further analyze relevant issues. To this end country cases of the semiconductor industry were partly covered by thus analysing the constraints and consequences especially for developing countries. For this purpose we carried out a search in TEXTLINE database which includes material of less technical character and more economics oriented nature which resulted in interesting references to material about the state-of-the-art in microelectronics in various countries (e.g. Malaysia, Singapore and South Korea).

Very valuable material, mainly about the Indian and Korean cases was obtained also from colleagues who are carrying out research on related issues at the Research Policy Institute in Lund. This material included, among other things, important information of statistical character. Since these researchers are well acquainted with the development of the microelectronics industry in developing countries, we also hope to draw benefits from their comments on this report for future revision.

In the beginning of the 1980s, UNIDO initiated a systematic effort to review and analyse the microelectronics sector and its implications for developing countries. Various reports were produced within different programmes such as the State of the art series on microelectronics. This series presents a description and analysis of the microelectronics sector in various countries.

Also the UNIDO/ECLA Expert Group has produced several reports dealing with the microelectronics industry and its implications for developing countries.

Reviewing some of these reports mentioned above we found that they are interesting each in its own way, but unfortunately, there seems to be no proper integration of the conclusions of all studies done by UNIDO experts up to date. Therefore, we regard all earlier UNIDO efforts as important for our study, since they set the point of departure for fruitful discussion and future development.

A successful effort by UNIDO to disseminate information and stimulate discussion about microelectronics is the MICROELECTRONICS MONITOR. This newsletter has a pleasant way of presenting different issues related to the microelectronics industry. The Microelectronics Monitor is published regularly presenting the trends in technological innovations, but it also has special issues which concentrate on specific related subjects.

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When approaching the subject of NC machine tools, we again had much assistance from various people. Mr Staffan Jacobsson's well documented knowledge of this field was a great resource. We also consulted people working at the Dept. of Production and Materials Engineering at the University of Lund.

The journals studied for this section were partly identified after a database search in COMPENDEX and INSPEC. The keywords used were as follows: "industrial robots", "numerical control", "NC", "CNC", "machine tool", "control system CAD", "controller", "process computer control", "CAM", "manufacturing computer control", "software".

Major journals for this technological field were Industrial Robot, Control Engineering, American Machinist. Groover & Zimmers' book on CAD/CAM has been a valuable reference volume.

IEEE has proved to be a very useful source for information, both regarding technical descriptions and general discussion.

Though not always mentioned as notes, sources of information regarding NC machine tools technology are listed in the bibliography.