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Very Large Scale Integration in Microelectronics (VLSI)

Preliminary Report

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Very Large Scale Integration
in Microelectronics
(VLSI)
Preliminary Report

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Ministry of State for
  Science and Technology,
Industry Branch,
Technology Assessment Division.

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OBJECTIVE

It is the intent of this report to assess the future of microelectronics at the VLSI (Very Large Scale Integration) level and to evaluate the desirability of a Canadian strategy in VLSI.

BACKGROUND

In 1948, a major technological breakthrough took place in the Bell Telephone Laboratories - the discovery of the transistor, a device capable of performing functions previously performed by the electron tube. Being a low cost electronic function, the transistor fostered the rapid development of electronic consumer products, computers and telecommunication equipment.

In the early sixties, another major invention took place. A few transistors and some passive components were produced on a semi-conductor chip to form a simple complete electronic circuit - the integrated circuit or IC.

The earliest integrated circuit chips contained just a few transistors; it was small scale integration (SSI). They were followed successively by chips containing a few hundred transistors (medium scale integration or MSI) and chips with more than ten thousand transistors (large scale integration or LSI. (Figure 1)

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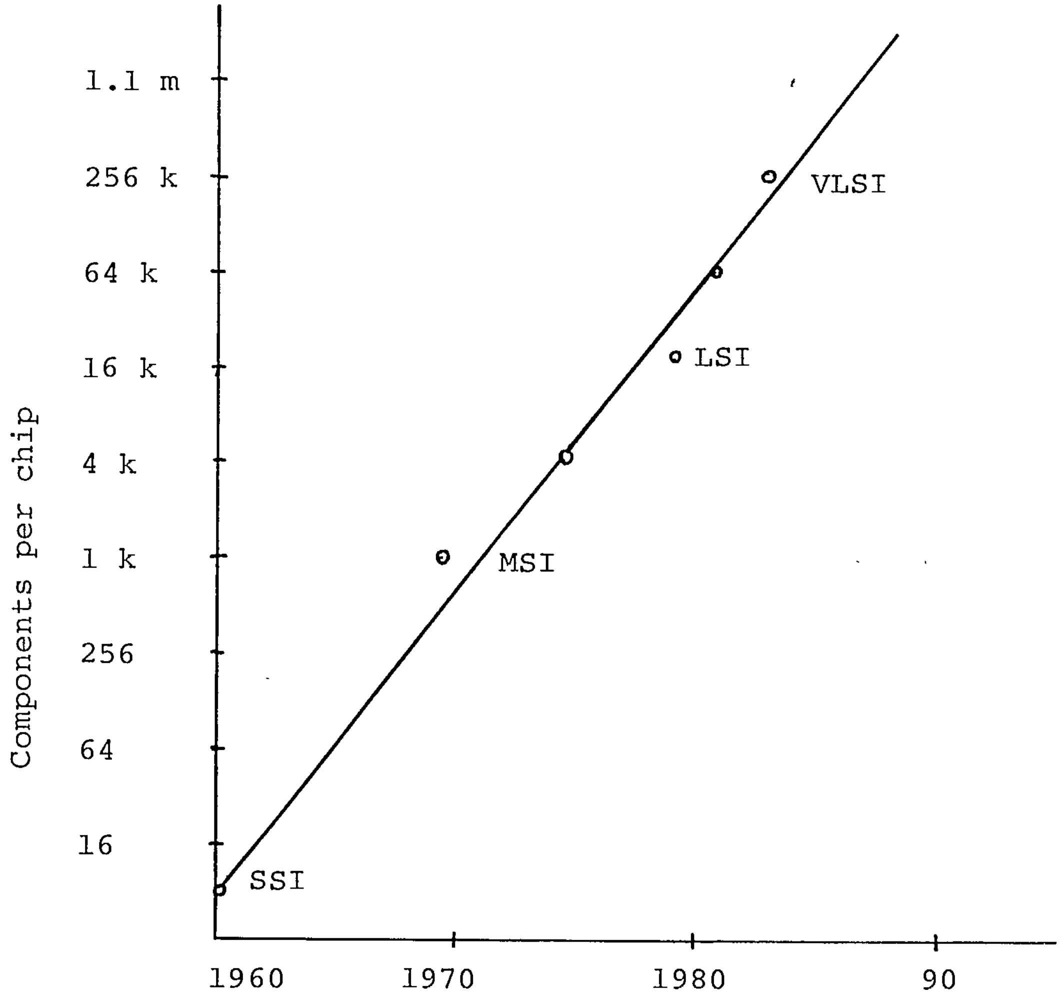

Figure 1: <u>Trends in chip complexity</u>.

Microelectronics is presently entering a new era; chips with more than a hundred thousand transistors. It is very large scale integration (VLSI). *

VLSI must not be seen as a discontinuity in the evolution of microelectronics. In fact, definitions of VLSI vary among different authors. VLSI is just a convenient way of defining a position on the integration level continuum so that the impact of its applications will be gradual and subtle rather than a quantum leap.

The introduction of increasingly powerful microprocessors or "computers-on-a-chip" will bring functions, whose performances were reserved for human beings, within the realm of electronics. "Intelligence" has been transferred on silicon and devices are no more restricted to perform a specialized task but their new flexibility permits them to perform a whole range of different functions. VLSI will take this capability still further.

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* Both Nippon Electric Company (NEC) and Oki recently announced production of a 1.1 M chip (1.1 million memory cells on a silicon dice only seven millimetres square) (The Economist, May 1, 1982, p. 93)

Each successive integration level greatly reduces costs per system. A $10 VLSI chip will do the work of maybe eight lower density chips which cost $2 each, for example, plus the cost of mounting them on the board. The reliability of systems will then be improved because welding points on pins are a potential source of system failure.

The size of systems will be reduced which is an important asset in many applications ranging from pocket calculators to aircraft guidance systems. By reducing the surface occupied by each transistor, the power requirement per element will be lowered and the operating speed will increase.

A previous report published by the Ministry of State for Science and Technology on the applications of microelectronics concluded that a Canadian strategy should be oriented towards applications in the following sectors: communications, data processing, office equipment, robotics and miscellaneous products incorporating microelectronic elements. This is a priority but a Canadian strategy has yet to be developed to ensure supply of chips for those applications.

In the first section, this report will outline the rationale for VLSI and it will survey possible applications of VLSI

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technology to sectors chosen as core technologies for Canada * . In the second section, advances in microelectronics will be reviewed. Finally, an overview of the industry will be presented, Canadian expertise will be assessed and options will be described.

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* See Applications of Microelectronics in a Canadian Context. MOSST, May 1981

RATIONALE FOR VLSI

To understand the phenomenal growth of microelectronics, one has to understand the revolutionary advantages brought about by this technology. It is the objective of this chapter to summarize this topic.

In the preceding pages, it was shown that the transistor replaced the vacuum tube because it was much cheaper - a few cents as opposed to a few dollars. One has just to examine any vacuum tube to realize its complexity and, consequently, its high cost of fabrication.

The evolution to microelectronics drastically reduced the price of each electronic function. Each chip, independent of its complexity, must be mounted in an individual casing to facilitate both its handling and the electrical connections to the outside world. Since it does not cost much more to package a 10,000 transistor chip than a 10 transistor chip and since the functional interconnection of transistors is part of the chip manufacturing process, the cost reductions are dramatic.

There is also another reason for the low cost of advanced microelectronic based systems. When five 100,000 transistor chips replace five hundred 1,000 transistor chips, a smaller

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mounting board is needed and the wiring of all these chips is greatly simplified. Then, there is a saving in support materials.

The price reductions have been phenomenal. As shown in Figure 2, the price per bit of information has dropped from 0.5 cent in 1973 to some 0.03 cent in 1980. Demonstrated another way (see Figure 3) the price of a 64K memory has been reduced from $110 in 1979 to some $8 in 1982.

The above discussion was restricted to the cost reductions experienced in electronic functions but the advantage of microelectronics can also be extended to mechanical devices.

It was soon realized that chips could not only substitute for older electronic functions but they could also replace some mechanical devices such as timers and cycle controllers in products as diverse as dishwashers and traffic light systems. Microelectronics is often a cheaper alternative because a few chips can replace complex assemblies of gears and other moving parts. The saving is double - the cost of material is often cheaper and the productivity in manufacturing is increased.

Another important factor of development is the reliability of integrated micro-circuits as opposed to vaccum tubes which

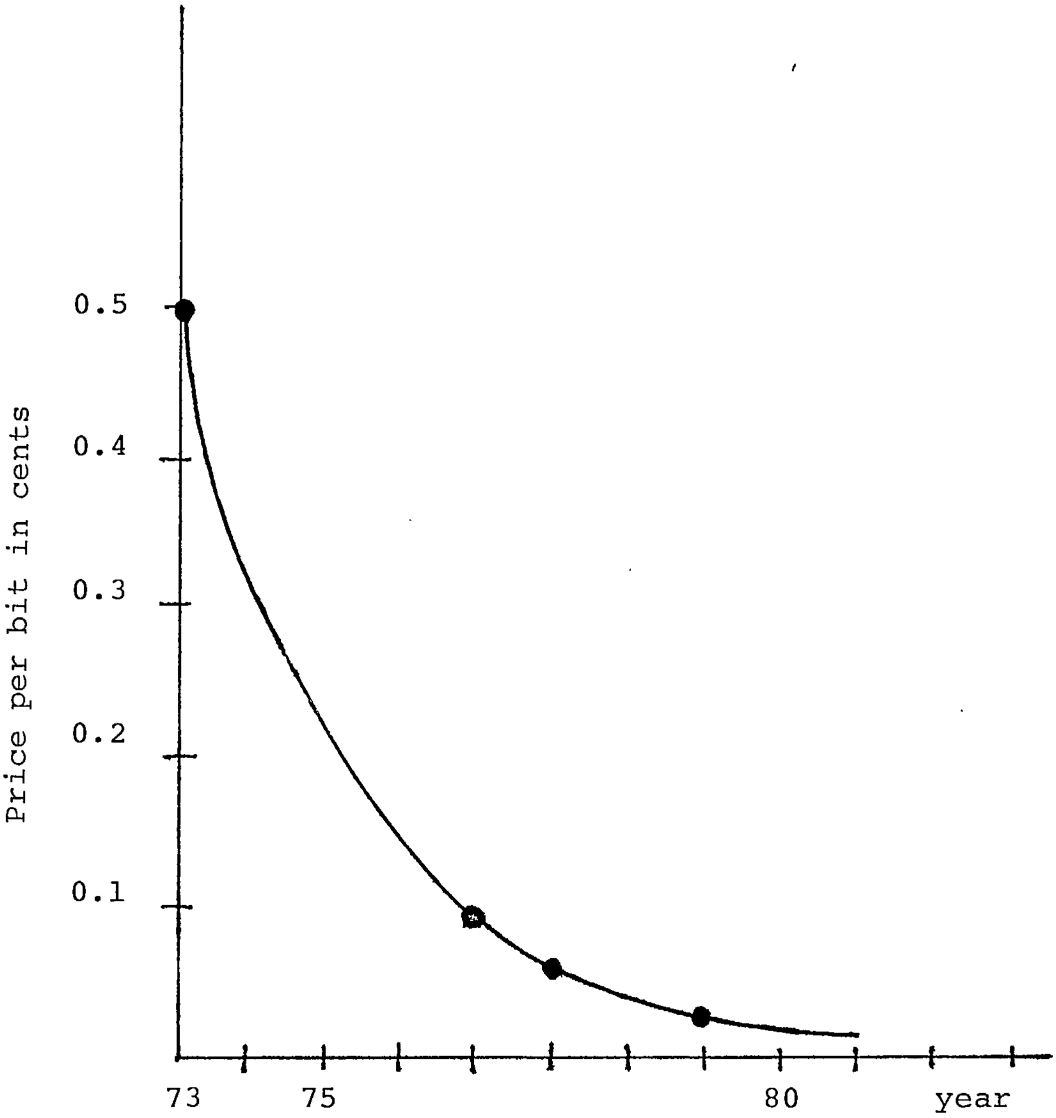

Figure 2: Price per bit

(Source: VLSI MOS RAM Market - Status and Future, p. 8 and Report of the Advisory Group on Microelectronics, p. 24)

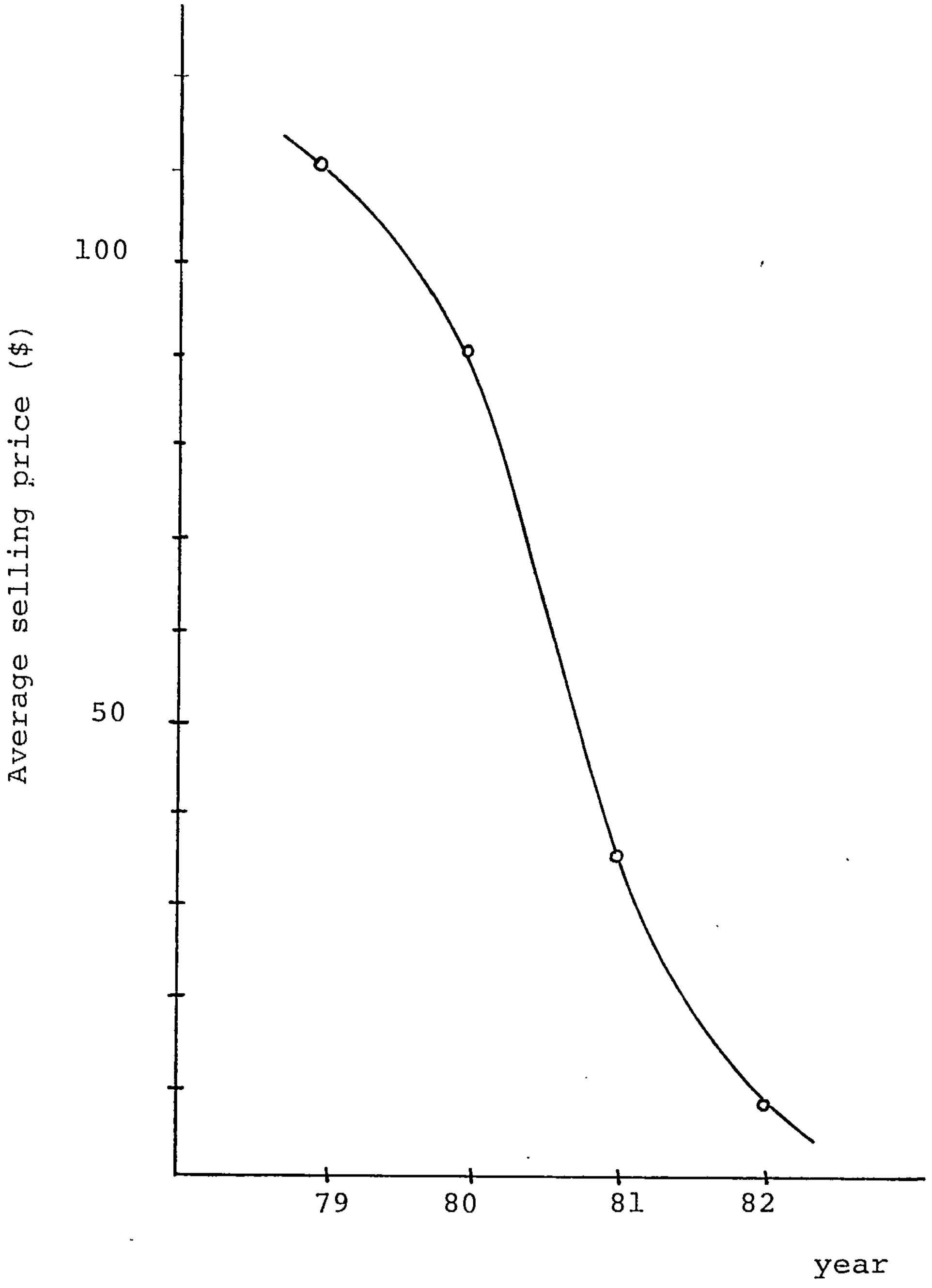

Figure 3: Average selling price of 64K memories

(Source: VLSI MOS RAM Market - Status and Future, p. 25, "The 64K Question", The Economist, May 15, 1982 and "Japan's Battering Rams", The Economist, June 13, 1981)

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are subject to burn-out. For example, the first computers were out of order most of the time because out of a roomful of vacuum tubes, there was almost always one which needed to be replaced.

System failure can also occur when interconnections become loose and the electronic signal is consequently switched off. In integrated circuits, these interconnections are an integral part of the chip, and once made, cannot be broken except if burnt-out like a fuse. The only interconnections subject to failure are the pins which make contact with the other parts of the system. If a VLSI chip can replace five LSI chips, there is then five times less the number of pins to cause a potential failure (the condition being that the number of pins per chip remains constant).

Finally, when chips are substituted for mechanical parts, reliability is greatly improved because moving parts are known to be subject to wear and to costly break-downs.

It should be remembered that for certain applications such as telecommunications, reliability is of utmost importance for commerciability.

Since microelectronics can integrate a large number of

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electronic or mechanical functions on a chip, products using such devices can be made much smaller and lighter. For example, the first computer filled a huge hall and was less powerful than today's pocket calculators. One can now have a fairly efficient computer on a desk. Without microelectronics, a Telidon decoder for example, would use much of the space in a conventional home basement (or more). As an additional example, Figure 4 shows the evolution in the size of a computer's main memory.

Since the surface actually occupied by each transistor is drastically reduced in VLSI, each transistor can be driven by much less power. In addition, smaller devices are inherently faster than larger ones - the current can switch them faster because of their lighter load. Another important factor comes into play in regards to smaller devices.

Since the speed of operation is limited by the speed of light (and actual speeds are much slower), smaller devices are faster because they are packed much more tightly (and thus the signal travels a shorter distance between devices).

These reductions in size and weight (together with low power requirements and high reliability) have been critical for the development of a viable satellite telecommunications system.

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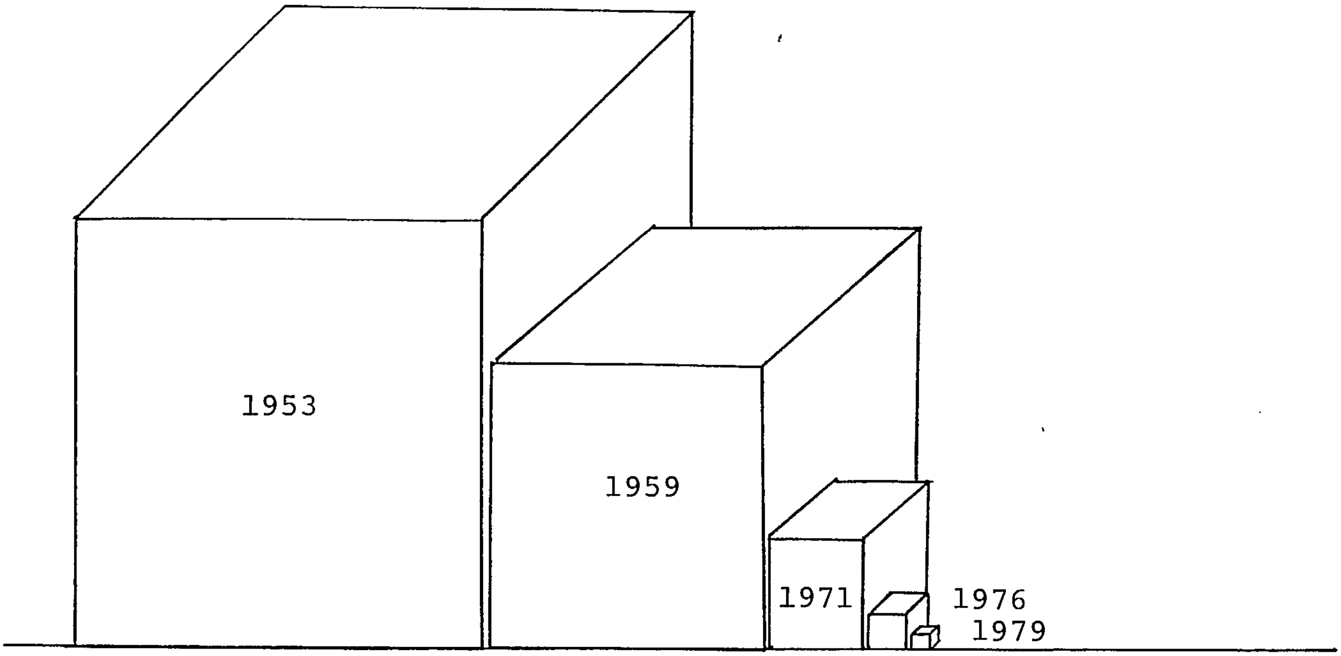

Figure 4: Evolution in the physical size of 1 megabyte of main memory. (Source: *Fortune*, May 31, 1982, p. 22)

As indicated in the introduction of the report, the evolution towards VLSI (and ultimately toward ultra or extreme high scale integration) will generate a wealth of new functions which are limited solely by our imagination. Some of these functions are already making an appearance on the market. In the kitchen, the name of the food to be cooked is entered into the microwave oven and the parameters are automatically set. Children can be taught spelling with Texas Instrument's Speak'n Spell. In France, a trial is being made with debit cards - a device like a credit card with a microprocessor embedded in it to record money transactions and to transfer funds into the store's bank account. Such examples can be found everyday in newspapers.

"Intelligent telephones", "intelligent this or that" are buzz words these days. Taken in this context, "intelligence" is simply any function which was previously done by human beings. These automated functions are still extremely trivial, as with, for instance, automatic phone dialing after a name is entered or redialing until a number can be reached.

As the technology proceeds from one integration level to the other, more and more logical functions can be built directly into the chip. With the advent of VLSI, it can be hypothesized that slightly higher human functions will be automated.

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To summarize, with microelectronics, devices are made much smaller, lighter, cheaper, faster, more reliable and power-efficient as integration levels evolve towards VLSI. Future chips will contain many more functions and the limit to these trends cannot be seen yet.

APPLICATIONS

In this section, applications of microelectronics which have been chosen as most appropriate for Canada in the report "Applications of Microelectronics in a Canadian Context" (MOSST, 1981) have been reviewed to assess the impact of VLSI on their development. They are: communications, computers, office equipment and robotics.

In "Applications of Microelectronics in a Canadian Context", miscellaneous products incorporating microelectronic elements were chosen as a promising sector. They were not discussed in the present report because the impact of VLSI on these products is still highly uncertain.

Everybody agrees that VLSI will have a very important impact on microelectronics applications but the technology is so new that just a very general survey of potential applications can be made. For this reason, this chapter is a summary of the technological content of the above-mentioned report.

1.0 Communications

Communications are an essential aspect of the information technology. Telephones, television, computer networks, electronic mail and electronic funds transfer are now all dependent on both communication technology and computer technology.

Microelectronics has had a huge impact on communications. First, it reduced the cost of communication equipment on terminals which provide the interface between people (or machines) and communication channels, on switching machines which establish the link, and on the equipment that processes signals so that they can be transmitted. Second, microelectronics improved the reliability of communications because chips are less subject to failure than discrete transistors. Finally, by reducing the size of equipment, microelectronics was an important factor in the development of satellite telecommunications.

With the advent of VLSI, the next decade will witness the widespread emergence of new services such as interactive terminals (Telidon), facsimile terminals, electronic mail and many other devices, all fitted in their own premises and operated over the public or private telecommunication networks.

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Communications will be flooded with new products - intelligent telephones which remember frequently-called numbers, electronic switchers to forward calls automatically, mobile terminals and many others. Some of these products already exist and will be made cheaper, smaller and more efficient with VLSI while others will be completely new products.

An area where VLSI will have a strong influence will be communication satellites and associated systems. Since cost is important and is directly related to the size and weight of the electronic components, microelectronics was a driving factor in the development of satellite communication networks. In addition, without the reliability of integrated circuits, it would have been almost impossible to make viable satellite systems. The present trend to VLSI chips will accelerate the development of communication satellites, earth terminals and peripherals, by reducing costs and weight, and by improving capabilities.

In order for information systems to reach their full potential, there must be a proliferation of simple-to-use terminals at a cost within the reach of the average Canadian. In August 1978, the Department of Communications announced the introduction of Telidon, a second generation videotext system. VLSI will permit

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the next generation of Telidon terminals to provide new functions like terminal-to-terminal communications at a much lower price so that Telidon terminals could be as common as television receivers and telephone sets in the not so distant future.

Today, computers can communicate between themselves and distant terminals. Electronic mail and facsimile transmissions are emerging. VLSI will have a marked impact on this broad class of equipment; multiplexers will be cheaper, network controllers will be "smarter", modems will be built into terminals, front end processors will be included in the communication network itself or in PBXs (Private Branching Exchange). In fact, "intelligent" PBXs will handle data and word-processing communications in addition to complex telephone operations like choosing the least costly line for long-distance calls.

2.0 Computers

Today, it is impossible to find any task which requires the processing of large amounts of information that is not performed by a computer. Lesser tasks are also being taken over by computers. Microelectronics increased the performance of computers, reduced their size and drastically lowered

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their price. Those factors have been the most important for the development of mini and micro-computers.

All computer systems, regardless of their size, consist of four basic elements: input-output ports, memories, a central processing unit (CPU) and peripherals. In the present section, the last three will be analyzed.

2.1 Central Processing Unit (CPU)

The principal impact of microelectronics on the CPU was to greatly improve performance because smaller devices are inherently faster than larger ones - the current can switch them faster because of their lighter load. As an example, the time required to execute an operation, for a mainframe computer, has dropped from 150 nanoseconds in the early 60's to 5 nanoseconds today. VLSI will improve speed but not in such a dramatic way as has microelectronics in the past.

Microprocessors have taken over the CPU and helped to develop new architectures. Arrays of microprocessors now replace the complex circuitry of the past. In one design, microprocessors are assembled one after the other and each one performs an operation on the data before

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transferring the results to the next processor like an assembly line. Another design consists of an array of microprocessors; all the microprocessors do identical processing on many data. Some microprocessors perform special functions like instruction fetching, control of the arithmetic logic unit and others.

One important measure of computer capacity is the number of binary digits which can be processed simultaneously because this influences the speed at which large numbers are calculated. The first microprocessors had a width of four bits and the actual standard is eight bits. Sixteen bit microprocessors are now available and, recently, Intel and Hewlett-Packard each announced a 32 bit microprocessor or the equivalent of a mainframe computer. (1) The Intel system uses three chips and the Hewlett-Packard system, six chips, one of which has some 600,000 circuit elements. Therefore, cheap mini-computers as powerful as recent mainframes could emerge around the end of the decade. This development would not have been possible without VLSI.

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(1) "Micro-Mainframe is Newest Computer on a Chip". Science, May 1st, 1981, p. 527-529.

2.2 Memories

The general principle of storage is to "write" data electrically or magnetically in a specific physical location in the memory which can be addressed in the same way a word can be specified by a page and a line number.

The technology of digital storage is the most rapidly changing sector in all microelectronics. In electronic memories, because of the regularity of the storage array, cell design can be optimized and very high component densities can be achieved. <u>This area will be the proving ground of VLSI technology</u>. State-of-the-art RAMs* have presently a capacity of 64K bits, and the Japanese are rumored to have an experimental 1100K VLSI memory. These VLSI memories may not appear as soon as predicted partly due to bit-error problems caused by alpha-particles on the very densely packed microcircuits. In any eventuality, VLSI memories will drive storage costs down, improve the storage capacity of small systems and eventually make magnetic storage obsolete.

VLSI could also give rise to less evident developments in memory technology. As the storage capacity increases,

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* Random Access Memories

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more on-chip logic will be incorporated to give a more powerful interface, through, for example, multiported operations, error detection and correction, and access by name rather than address.

2.3 Peripherals

Peripherals include all ancillary equipment necessary to fully use computers. Examples include external memories, data entry and data output equipment.

VLSI will permit the introduction of cheaper terminals, optical character reading systems and other add-on devices. In fact, France's Alcatel Electronique is currently selling a small, cheap video terminal complete with keyboard and CRT for $200. Its target price for 1983 is $100. (2)

There is a trend today toward distributing the processing of some information throughout the computer system to bring some relief to the CPU. VLSI will foster an explosion of "intelligent" disk drives with functions like error-correcting, preliminary processing of data through "smart" terminals and many other functions.

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(2) "An Export of Low-Cost Terminals". Business Week, May 11, 1981, p. 46.

A word of caution should be added. With VLSI chips, it could become attractive for computer manufacturers to bury their operating systems in the hardware, thus preventing plug-compatible companies from producing equivalent products and locking users to manufacturers more rigidly. This will threaten peripheral manufacturers if it ever happens.

3.0 Office Equipment

Automation in the office is the natural consequence of the desire to increase productivity and efficiency through the integration of different communication tools because communications absorb almost two-third of manpower costs in today's offices.

This evolution has already started with the word-processor. A document can be electronically memorized and, subsequently, the typist can introduce corrections, additions, or can delete words or whole paragraphs before having the machine print the final copy. The word-processor can automatically paginate the document after having divided the text into pages of specified length. It can edit and merge different parts of the text to form a new document. It can also sort and select files in numerical or alphabetical order.

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Finally, some units have arithmetic and statistical capabilities to perform arithmetic tasks, print statistical tables and complex equations. The text is automatically printed, simply displayed on a CRT screen for consultation or sent electronically to the other end of the country where a similar machine can print the text. Text processing can now be interfaced to data communications, so that the future points to a growing participation of different technologies in establishing an integrated office environment.

The impact of VLSI on office equipment will be similar to the impact on communication equipment and computers but clarification should be given about the price of equipment. Microelectronics development to LSI (and to VLSI in the near future) through cost reductions per byte, has shrunk word-processing hardware costs from some $40,000 five years ago to $ 8,000 today. A variety of factors will prevent a further decline in price, the main one being the increasing cost of software compounded by a shortage of qualified programmers. This cost will be counteracted by decreases in the cost of hardware, particularly in memories which are the proving grounds of VLSI technology.

On the other hand, thanks to VLSI, future word processors, for the same price, will be equipped with more capabilities

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and new functions. A new trend is also emerging with the development of total word processing/data processing information systems. File management, electronic mail, smart photocopiers and automatic telephone switching equipment (PABX) will certainly become integrated to word processing in the near future so that future equipment will have to incorporate communication capabilities.

4.0 Robotics

Today's robots are not yet the version popularized by Hollywood and they will not be at least until the next century. Industrial robots may best be described as an artificial arm or hand, driven electrically, hydraulically or pneumatically and controlled by a computer to perform a number of co-ordinated operations of a repetitive nature on a workpiece.

Up to now, the introduction of robots on the shop floor has been rather slow for a number of reasons. The major reason was that no factory would have dared to have robots controlled by a central computer as the whole production line would have been dependent on a single computer. VLSI will have a great impact on robots. The control unit will not only become much less expensive and more powerful , but it will be built directly into the robot so that the information

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is processed where the robot is without the necessity for central control.

By improving the capabilities of micro-processors and memories, VLSI will permit the development of a new generation of "intelligent" robots with quasi-human senses, like vision and touch which will have capabilities to adapt themselves to new situations. Robots can then be expected to become more versatile and less expensive with VLSI chips but the mechanical, hydraulic and electric constructions will be limiting factors in price reduction.

5.0 Conclusion

VLSI technology is still at the early stage of this development so that any attempt at predicting its impact on electronic goods and processes remains highly speculative.

However, it can reasonably be assumed that the most important applications of this technology will be in storage media for computers and word processors, and in more powerful micro-processors followed by applications of VLSI custom chips in communications.

On the longer term, VLSI will gradually influence the processing unit of robots.

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VLSI TECHNOLOGY

In the previous section, possible applications of VLSI chips have been reviewed. In the present section, an overview of the technology behind these chips will be presented.

The four broad classes of chips will first be introduced, and classes of technologies will be reviewed. VLSI technology will be analyzed both at the design and at the fabrication levels to evaluate the most recent developments in this technology and to introduce the reader to the problems which will have to be addressed in the years to come.

1.0 Classes of Integrated-Circuits

First, it should be noted that microelectronics are based on just four broad classes of components or circuits: microprocessors, specific or custom circuits, semi-custom chips and memories.

The microprocessor (the so-called computer-on-a-chip) is a universal circuit which can be mass-produced and then tailored to specific uses by adding the appropriate programs

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or instructions which are written in memories connected to the microprocessor. It provides intelligence at low cost for virtually any application. Another plus is that errors can be corrected by executing a simple program change rather than by "rewiring" or redesigning the circuit. On the other hand, even though microprocessors contain something for everybody, nobody wants everything on them. In addition, microprocessors process their instructions step by step which is considered to be an excessively slow method in many applications of microelectronics.

Another class of circuits is the specific or custom IC like read-only memories (ROM), signal processors, generators and detectors which are designed to accomplish a very specific application. As opposed to the microprocessor, the numerous logic functions are performed in parallel which increases the speed of operation.

As shown by Figure 5, each VLSI custom circuit can be applied only to very specific applications which limit their use while microprocessors are really universal. Custom circuits can be economically produced only in fairly large series.

A new class of circuits is now emerging: semi-custom

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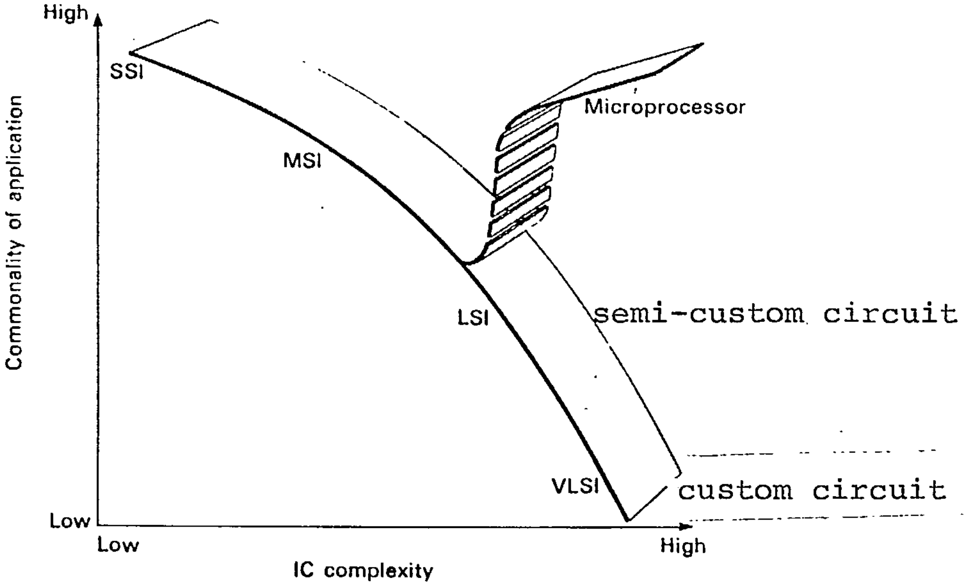

Figure 5: Commonality of Applications versus IC Complexity.
(Source: <u>The Microelectronics Revolution</u> Edited by Tom Forester, the MIT Press, 1981, p. 92)

circuits. These are basically general-purpose but incomplete chips consisting of simple functional units which are interconnected according to the design required for the application under consideration. These circuits are more specific than microprocessors but more general than fully customized chips. They are tailored for medium and small production runs.

A last class of circuits is composed of random-access memories (RAMs) in which data can be "written" and "read" selectively. These are essentially arrays of identical memory cells. They are used mostly for the temporary storage of data in computers.

2.0 Classes of Technologies

An avalanche of acronyms is necessary to describe all the semiconductor technologies used to produce the chips mentioned in the previous section. This subject, having been covered in a previous report published by MOSST (Microelectronics, March 1980), will not be repeated in the present report. Table I summarizes the advantages and the disadvantages of these diverse technologies.

Silicon has been, and is, the almost exclusive semiconducting material used in integrated circuits. It is plentiful,

			Advantages	Disadvantages
Silicon Technology	Bipolar Devices	TTL (Transistor-Transistor Logic)	Proven technology, 10-15 years old. High-speed 1.5-3N sec/gate 5V architecture can be used to drive other devices	High power consumption, 2-4 picojoule/ switch operation. Complex construction, employs 10 to 12 masking levels.
		ECL (Emitter-Coupled Logic)	Highest speed of commercially available semiconductor techniques. Operates at .4-in sec/gate. Can be used in high-speed cache memory applications.	High power consumption, 3-6 picojoule/ switching operation. Special voltage requirements.
		I²L (Integrated-Injection Logic)	Newest technology, still in evolutionary state. Low power dissipation, 0.5-1.5 picojoule/switching operation. Can be density packed. Low manufacturing cost can employ both analog and digital circuits, ideal for analog — digital converters.	Slow. Operates in the 2.5 to 10 nsec range. Small current user base promising, but uncertain future.
	MOS Devices (Metallic Oxide Semiconductors)	Nmos (Negeative MOS)	Chips are small. A large number of Nmos devices can be cut from a single silicon wafer. Low cost with a relatively high speed, 1 to 3 nsec/gate.	Higher power consumption through Cmos. Operates at 0.2 to 1.0 picojoule/ switching operation, but also has static power consumption — Cmos does not. Power consumption is low when compared to bipolar devices, however.
		Cmos (Complementary MOS)	Low power requirements. Operates at 0.1 to 0.3 picojoule/switching operation. However, static power consumption is virtually nil. High immunity to power noise.	Relatively high chip area. Costs more than Nmos. Expensive manufacturing process, eight to 10 masking levels. Lacks speed of Nmos. Operates at 2.5 to -10 nsec/gate.
		Pmos (Positive MOS)	First MOS technology. Inexpensive one- to three-masking-level manufacturing technique.	High chip area. Slow. Operates in the 10 to 30 nsec/gate range.
		Cmos SOS (Silicon-on-Sapphire)	Smaller chip area than Cmos. Radiation hardness, high resistance to alpha particles. Ideal for military or high-radiation applications. High voltage noise immunity. Speed in 1 to 6 nsec/gate range.	Expensive. Manufacturing process is difficult, usually a low yield of quality chips. Tends to be inflexible.
	Gallium Arsenide	GaAs	Fast. Operates at .2 to .7 nsec/gate. Moderate power consumption. Promising technology.	New technology, not commercially available. Cost high, but may come down. Manufacturing process difficult, low quality yield.

Table I: <u>Microelectronics Technologies</u>

(Source: <u>Computer World</u>, April 19, 1982)

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cheap and relatively easy to process. Another material is now being considered as an alternative to silicon: gallium arsenide.

Because gallium arsenide is about five times faster than silicon as a semiconductor switch (so it can transmit microwaves) and because it consumes less power (a prerequisite for satellite systems) this new material is the leading candidate for the next generation of communication satellites. Through this material, microwave signals could be received by roof-top antennas.

Another important property of gallium arsenide is that it can emit light. This material could then link electronic components with optical communication systems.

On the other hand, gallium arsenide is fairly rare - it costs approximately a thousand times more than silicon. The manufacturing process is difficult and the technology is still restricted to the medium-scale level of integration.

3.0 Design, Fabrication and Testing of Chips

All microelectronic circuits are designed and fabricated essentially by the same technological processes. In the present section, the current technology will be reviewed and

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future developments will be described.

The speed at which the complexity of integrated-circuits (IC's) increases may slow down somewhat with the advent of VLSI.

First, designing a chip with 100,000 transistors is necessarily more complex and more time-consuming than was the case for a chip with 10,000 transistors. Dennis Moralee recently used an analogy to illustrate the increasing complexity of IC design. (3) In 1963, a chip was like a street map representing 1 km^2. The chip of 1985 will be like an error-free map representing 62,500 km^2 with the same level of detail. To make matters even more complicated, a chip contains up to ten layers of such maps. Peter Benedeck of Bell Northern Research states that complexity increases at a rate of some 45% per year and the design effort is proportional to the square of complexity. Because no human can keep mental track of the details of VLSI designs, computer-aided design comes into play, but it is not certain if it will be sufficient unless an entirely new design approach - large-systems design methodology - is developed.

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(3) D. Moralee. "Visions of the VLSI Future". Electronics and Power, April 1982, p. 301-305.

Second, the evolution to VLSI necessitates significant reduction in device geometry and line width from 5-6 microns today to 1-2 microns tomorrow. To return to the street map analogy, the size of the map will remain constant but the details of the map will shrink so much they will have to be read with a powerful microscope. Lithography will then be a critical variable in the introduction of very high component packing densities. A solution which has been proposed consists of building the circuits in three dimensions rather than two, but it is still an abstract concept rather than an experimental reality.

A third factor will be that while packing densities increase as the square, the number of input/output pins (to address individual logic cells) increases only linearly. A solution to this problem may be to incorporate logic into the chip.

The whole technological process is schematically illustrated in Figure 6; the chip is designed, masks of the circuits are made, the circuit is "printed" on the wafer, technological operations are done and the chip is finally tested.

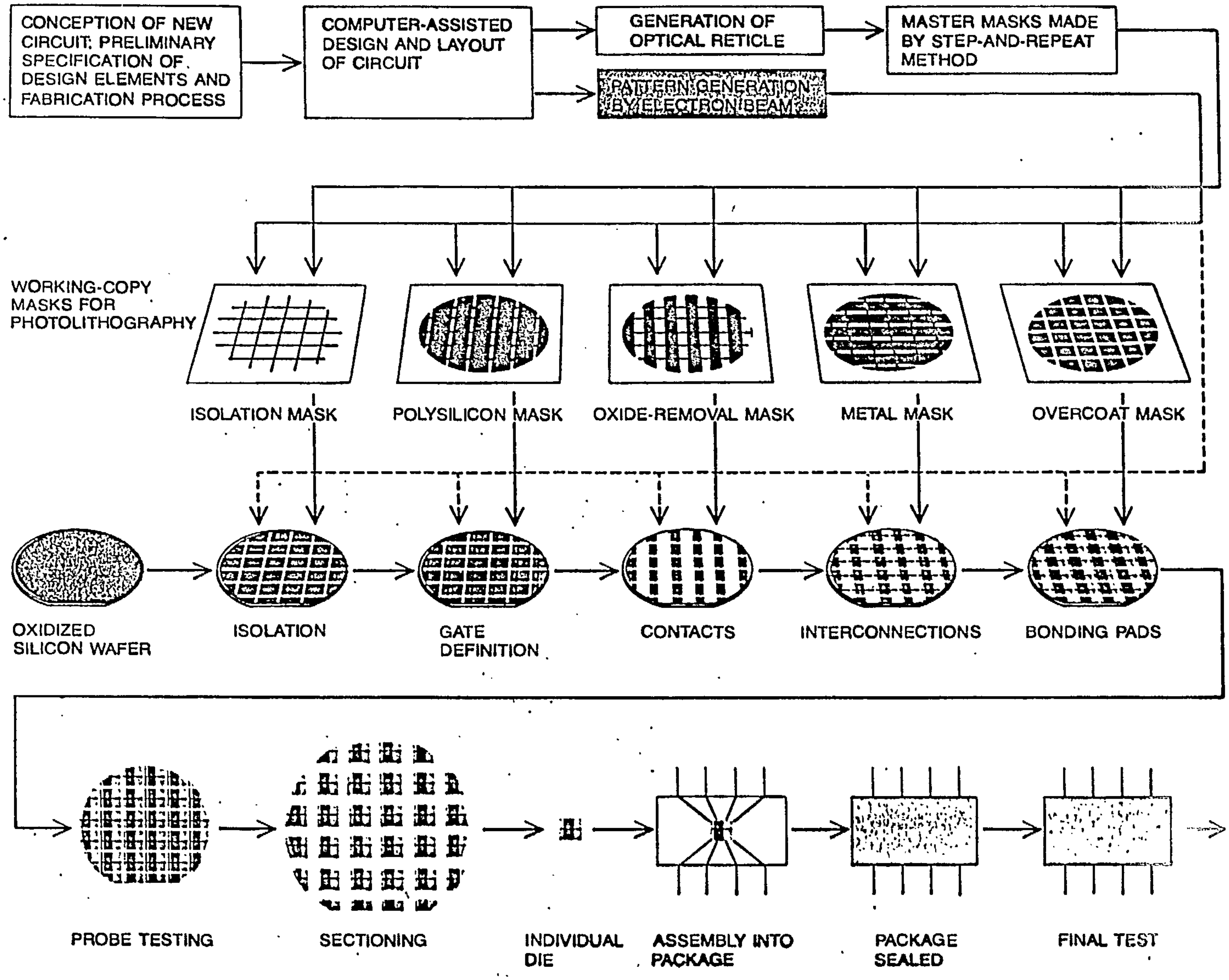

Figure 6: Design and Fabrication of Microelectronics Circuits. ~~(Source: W.G. Oldham. "The Fabrication of~~ Microelectronics Circuits". Scientific American, ~~September 1977, p. 112).~~

3.1 Design

With the increasing complexity of digital integrated circuits, the design process has become excessively complex and, at the LSI level, it can require an effort of many person/years. Today, with thousands of transistors packed on the surface of the chip, days where designers could work with pencil and paper are long gone. Design engineers are now helped by CAD (Computer-Aided Design) tools which will become a major necessity in VLSI technology.

The design process can be summarized as follows. The required function is defined, the gate level specified, and then the transistor level is described. Logic and circuit simulations are done, the layout of the circuit is prepared and checked for errors such as space violations.

3.1.1 Design

Engineers now have programs at their disposal which permit drawing of the circuit elements on a CRT terminal. They use symbols which are much less complex than the actual circuit elements. For example, a designer needs only use an

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electronic stylus or a cursor moved through a keyboard to choose gates needed for an array and the computer draws the details of the array. Those programs use elementary topologic figures (rectangles, polygons, lines, ties,...) and operations on those figures (fusion, translation, rotation, symmetry, repetition, intersection,...)

On VLSI circuits, many components such as memory cells, are identical, though they are laid out in arrays of tens or hundreds of thousands. The designer has just to draw the outline boundaries of one array on the video screen and the computer fills that array with hundreds of identical cells. It is easy to imagine the amount of time which would have been required to draw this circuit by hand.

3.1.2 Simulation

Each electronic function must be checked both at the logic and the electric level. Fortunately, the engineer is helped by CAD programs in the areas of analysis of process, simulation of device and circuit analysis at various levels (device

.../38

gate and system). The computer can simulate the operation of the circuit like electronic television games simulate the action of a space war for example. The behavior of the circuit is then monitored and adjusted on the video screen rather than on a "breadboard" circuit which considerably reduces costs.

At the present time, there is a certain number of programs available for process simulation (e.g. SUPREM), modelling and simulation at the device, circuit and subsystem level (e.g. SPICE, MOTIS, DIANA) and for logic simulation (e.g. I. LOGIC and F. LOGIC). Such programs are used by Mitel and Bell-Northern Research.

These programs have been easily available up to now, being freely distributed by the University of California, Berkley and Stanford University, but the user had to adapt them himself. As international borders are now closing to the free flow of such CAD programs, it becomes essential for Canada to develop capabilities in this important field.

3.1.3 Layout

When the design is done, it is drawn for future use. In the past, and some companies still do it this way, circuits were drawn at a thousand times their scale on clear plastic sheets to show every single component and connection. The sheets had to be carefully co-ordinated since there are different circuit patterns on the different layers of the chip. The physical problem of matching all those sheets is enormous and it will become economically impossible to use that old-fashioned process with VLSI chips.

CAD systems now in use automatically drive a tracing table to produce an error-free mask of the circuit.

3.1.4 Verification

Today, when a circuit is designed on a computer-aided design system, it is stored in the computer's memory.

Verification programs are then needed to check

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continuity (whether or not the logic or electric diagram corresponds to the original) and drawing rules (dimension and minimum spacing constraints).

Continuity checks previously done manually, requiring designers to inspect the sequence of thousands of transistors or logic gates on a copy of the layout enlarged some 500 times the final size of the circuit, are now done automatically.

Drawing rules verification presently make use of the computer's ability to review the completed design to ensure that all specifications are accurate. That verification is very important as an error in spacing as small as one micron can cause a short-circuit on the chip. A typical integrated circuit requires only about 30 hours of computer time to check the circuit, as opposed to 20 weeks needed by a team of humans. A fortiori, with the advent of VLSI, drawing rules testing by computer will become a necessity.

Although the packing of the circuit will have been optimized by the system, the design produced may not be the best layout.

Automatic or semi-automatic positioning and inter-connecting programs can sometimes be used, but until additional development occurs in the field of artificial intelligence, those algorithms will not replace the human eye and brain even when used with powerful computers.

The area of testing has become of major importance to the microelectronic industry with the increasing complexity of the circuits. With VLSI chips, it will be impossible in the time frame available to a manufacturer to do a complete testing for all possible errors which might exist. The trends which are now emerging are to develop testing algorithms which uncover the most significant faults or to incorporate, in the chip design, the facility for self-testing.

3.1.5 Conclusion

It has been estimated that future circuits like 32 bit microprocessors would require an effort of the order of 300 man-years to design. The solution lies in the development of better CAD tools using principles of artificial intelligence and new logic and electric structures.

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It should be noted that these CAD systems are fairly expensive. A system similar to that used by Mitel in Bromont (computer, terminals, tracing table and software) costs approximately $450,000. On the other hand, thanks to advances in microelectronics, prices are coming down. For example, Calma is selling a CAD package called STICKS for $80,000 (U.S.).

Finally, it is important to note that the skills required in design are changing from the traditional electronic engineering design background towards more computer science knowledge. Figure 7 illustrates this need. It describes the design of a 4-bit register and a register file of 16 of these units. This design is done using a programming language (Inmos Hardware Design Language) rather than geometric symbols.

3.2 Lithography

Making an integrated circuit is a series of simple steps. Generally, a mask representing the circuit to be drawn is "printed" on the chip by a lithographic process and the elements of the circuits are subsequently

.../43

built directly on the chip. Details of this process will now be discussed and future orientations will be considered. (See note)

```
MODULE REG (IN input [0:3), clock_, enable,
                 OUT output [0:3] )

   SIGNAL gated_clock = UNE (enable, clock_)

   output = UNE (INV (gated_clock@[0:3] ), input),
              UNE (gated_clock@([0:3] , INV (output))

END REG


MODULE REG_FILE (IN addr[0:3] , input[0:3] ,
                            clock_, write_enable,
                         OUT output[0:3] )

   SIGNAL control [0:15] = DECODE4 (addr),
            ram [0:15] [0:3]

   FOR i = [0:15] DO
      NE (control [i] @[0:3] , ram [i] ,output),
      REG (input, clock_,
            UNE (write_enable, control [i] ), ram [i] )

END REG_FILE
```

Figure 7: <u>Design of a 4-bit register and a register file of 16 4-bit registers.</u> (Source: D. Moralee. Op. cit., p. 305)

3.2.1 Substrate

Silicon is the substrate most widely used by current technology. A number of steps are necessary

.../44

NOTE: All the fabrication process is performed in dust-free rooms to avoid contamination and dust defects.

to obtain the wafers on which chips are made. A cylindrical silicon ingot is first made by inserting a "seed" crystal in molten silicon, which has previously been reduced to elemental silicon. It is then purified and doped with selected impurities. The crystal is then repeatedly pulled out. The ingot is ground to obtain a standard diameter. The present diameter of the ingot is 4 inches but it should increase to 5 and 6 inches in the near future. Wafers are cut and polished and a coat of silicon dioxide is formed on their surface by oxidization at high temperature. The oxide layer will later act as a mask for selective doping and as an insulator. It should be noted that the chemical composition of the substrate has to be monitored very closely.

Recent developments point to the fact that silicon might eventually give way to more complex materials like gallium arsenide which could be used for a new class of ultra-high-speed VLSI devices. As a semi-conductor switch, it is about five times faster than silicon. Since gallium is fairly rare and gallium arsenide is a difficult material to work with, it will likely be confined to high performance systems. (See note)

NOTE: Cominco recently opened a new gallium arsenide plant in British Columbia.

Another recent development is the use of an insulating substrate like sapphire where silicon films are grown on this material. CMOS* circuits fabricated with this method offer a high packing density, and therefore, a very high performance technology which is likely to become increasingly important for high performance systems in the 1980's.

3.2.2 Lithography

Lithography plays a central role in integrated circuit fabrication by defining the layout of the circuit on the silicon substrate. Usually, a coat of light-sensitive polymer (photoresist) is first deposited on the silicon wafer. (The essential property of the photoresist is that its solubility in certain solvents changes when exposed to a light source). A mask containing the layout of the circuit is placed between the light source and the substrate covered by photoresist, so that the layout is photo-engraved on the substrate. A suitable solvent then removes unexposed parts of the photoresist. The circuit pattern is now left on the surface and hydrofluoric acid will attack

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*CMOS: Complementary Metal Oxide Semiconductor

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the bare silicon dioxide layer where photoresist has been removed (the photoresist and silicon are not attacked by the acid). A technological operation is then done (oxydation, doping or electrical connection deposition). The process can now be repeated to build the other layers which will comprise the final circuit. The process is illustrated schematically in Figure 8.

Since the chips are always of the same size and since line width has been reduced to some 3 microns and will shrink to a mere micron at VLSI levels, lithography has become a critical step in the emerging VLSI technology.

3.2.2.1 Mask Generation

The first step of the lithographic process consists of drawing a mask of the circuit (see Figure 6, p. 35). In the past, masks were drawn by hand but with the advent of LSI technology (and VLSI) almost all masks are made by mechanical pattern generators which are complex photomechanical printers controlled by computer.

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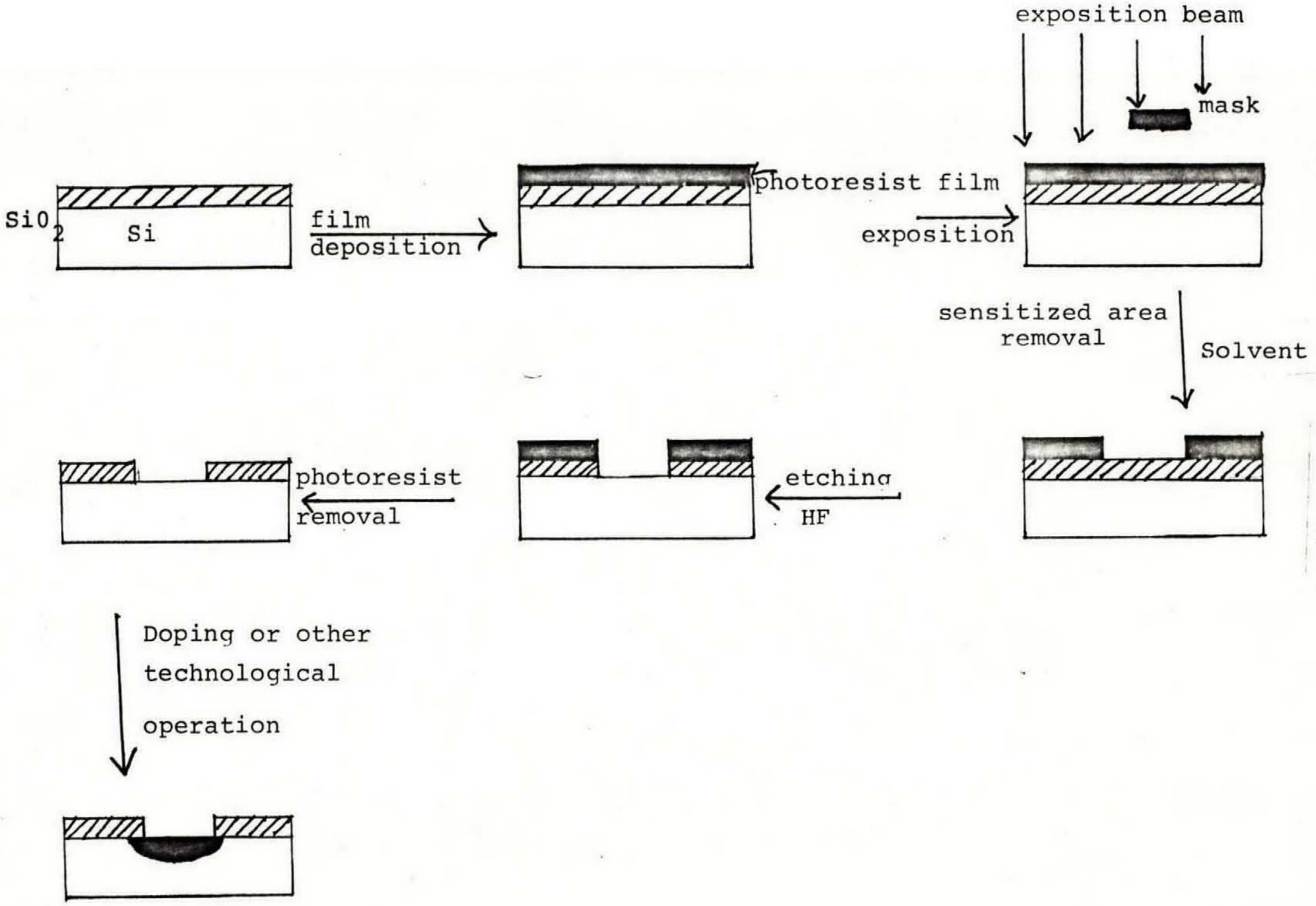

Figure 8 · <u>Lithography Process</u>

(Ref. <u>The Microelectronics Revolution</u>, p.51)

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A typical silicon wafer contains a few hundred identical integrated circuits. Two kinds of techniques can be used to make a mask. In one technique, to be discussed later, a mask of a single circuit is made and the wafer is subsequently displaced to expose each successive circuit. In a second technique, the mask of one circuit is produced, checked for errors and corrected. This mask is called a reticle. The reticle is then photographically reproduced side by side by a step and repeat camera to produce a mask that will contain all the chips to be produced on a single wafer. The whole wafer is exposed just once. This process is very expensive as it takes 40 hours or more to make each mask or several hundred hours for a complete set of masks for a typical multilayer integrated circuit.

As masks have sometimes to be modified during pilot production and as new devices have to get into market very quickly, the great complexity of VLSI circuits will make this technique uneconomic in the near future.

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A new technology, electron-beam pattern generation, is emerging to replace older mechanical pattern generators. It could be used to produce the mask for a single chip or for the whole wafer. The generator is simply a high-intensity electron gun usually adapted from a scanning electron microscope. It is used to project a beam of electrons on a mask substrate sensitive to electrons and held in an evacuated enclosure; essentially, light is replaced by electrons. Because of limitations in the amount of deflection which can be applied to the electron-beam, the actual writing is confined to an area of the order of 1 square mm. so that the mask substrate has to be mechanically moved to write the adjacent area, the mask position being sensed by a laser interferometer controlled by a computer.

This technology permits the production of very-high-resolution masks with line width as small as 0.1 micron, but the main advantage of this technology is its high writing speed. While it took some hours to produce a

.../50

single mask by mechanical pattern generators, it takes only 20 minutes by electron-beam generation. The main limitation of this technique is its basic price which is in the order of one million dollars. It is generally believed however that electron-beam pattern generation will be the technique used by VLSI.

3.2.2.2 Printing

The mask of the circuit can now be printed on the wafer (see Figure 6, page 35). Up to now, the most widely used lithographic technique has been contact printing where the mask carrying the pattern of the circuit is placed in contact with the layer of photoresist (sensitive layer) formed on the surface of the wafer. As today's circuits get more complex and line widths shrink toward the wavelength of visible light, diffraction effects occur which destroy the resolution. It is as if the circuit elements are so close together that light cannot pass between them. With LSI technology, ultraviolet light (smaller wavelength) is used to avoid this problem. The line width limit then seems to hover around 3 microns.

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To make a chip, the wafer goes through a cycle of pattern printing (through mask exposition) followed by etching and doping of exposed areas. As successive layers of a microelectronic circuit are built up, this cycle has to be repeated up to a dozen times, each time with a different mask appropriate for the technical operation to be performed. Contact aligners are used to accurately align the new mask with work already done on the silicon base. They are simple and relatively inexpensive ($20,000) but they will be of no great use in VLSI technology since realignment more accurate than 1.5 microns is not currently feasible.

There is another reason why this technique will not be used in VLSI technology. Each time the mask is brought into contact with the wafer, inevitable damage is caused to its surface. The next time this mask will be used, the defects will be printed onto the wafer, with the defects being additive. As line widths are reduced, chances of a scratch ruining the circuit are increased.

At lower integration densities, each mask has a useful life of 25 to 75 expositions. It should be noted that these masks are not expensive master masks but inexpensive copies produced by a mask duplicator from submasters. The expense of duplication is no longer necessary, as better technology is available. Two new techniques have been developed to prevent contact of the mask with the wafer; projection-alignment and step and repeat projection.

The first technique developed, projection-alignment, is simply the optical projection of the mask on the wafer which avoids mask-wafer contact problems. The mask contains the hundreds of chips to be projected on each wafer. A first advantage of the technique is that it permits printing of the whole wafer in a single step. Another advantage is that the projected image can be adjusted in size to correspond exactly to the size of the wafer to be printed.

As initially developed, this technique

.../53

presented many flaws. With modern line widths and wafer size, available lenses do not have the necessary resolution. Another difficulty was that the best optical glasses are more or less opaque to ultraviolet wavelengths. It has previously been seen that ultraviolet is necessary at scales of large integration.

These problems have been solved with the introduction of the Micralign Projection Aligner (Perkin-Elmer Corporation) which uses reflective optics instead of transmitting optics. It projects only a narrow slit on the wafer, but by moving both the mask and the wafer past the optical system, the whole surface of the wafer is eventually exposed.

Resolution is presently in the order of 1 micron on a wafer of a diameter of 5 inches. Resolution improvements are expensive; projection aligners cost around $200,000 as opposed to $20,000 for a contact aligner. It should be noted that coupling the projection aligner with an automatic wafer handler permits exposition

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of 60 wafers per hour at actual line widths.(4)

A more recent approach to projection printing is the step and repeat projection or direct-step-on-wafer (d.s.w.). A mask of a single chip (reticle) is projected over the wafer and the wafer is then displaced to print adjacent chips until the whole wafer has been printed. Commercially available lenses are precise enough to permit a resolution of 1.3 microns. Since the reticle is used directly, extra processing steps are avoided and the effects of dust particles on the mask are greatly reduced.

Actual step and repeat projection systems cost approximately half a million dollars and output is lower than for projection aligners (10-60 wafers per hour) even though they use a much more intense illumination.(5) Their advantage is the higher yields of fault-free chips.

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(4) L.N. Jackson and P. Leigh-Jones. "Electronic Technology in Australia". Technological Change in Australia. Australian Government Publishing Services, Canberra 1980. Volume Four, p.14.

(5) L.N. Jackson and P. Leigh-Jones, Op.Cit., p. 14.

The main problem of projection techniques is the alignment of successive masks which could be done automatically by lasers in the next few years.

The use of X-ray instead of ultraviolet light would avoid the diffraction effects at higher integration levels. The mask, made of ultra-thin metallized lines generated by an electron-beam equipment on an X-ray transparent film, will have to be in contact with or very close to the wafer, since there is no way to focus X-rays (they radiate from the source in a cone like the light of a flashlight). By minimizing the distance between the mask and the wafer, diffraction problems are reduced because of the short wavelength of X-rays. In fact, submicronic resolution is expected and output should be some 75 wafers per hour according to the latest estimates. (6)

IBM has recently announced the development of a relatively inexpensive plasma-based X-ray

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(6) G.P. O'Clock and R.J. Herickhoff. "Making Better Chips Gets More Difficult and More Costly". Industrial Research and Development, June 1982, p. 116.

.../56

gun which could expose a whole wafer in a fraction of a second. It is generally estimated that X-ray systems could be commercially available by mid-1980's. One of the real problems which will have to be solved, will be how to align successive masks on the wafer if they have to be positioned within a distance of less than the wavelength of visible light. It has been suggested that automatic diffraction-pattern sensors could possibly be used.

A new technique developed by Philips is the electron image projector. A conventional chrome-on-glass mask, coated with a thin caesium iodide photocathodic layer, is illuminated with ultraviolet light. This layer causes the opaque areas of the mask to emit photo-electrons which are accelerated and focussed on the wafer by a magnetic focussing system similar to lenses used in electronic microscopes. The alignment problem has been solved by incorporating tantalum markers on each wafer exposed. Those markers emit X-rays when hit by electrons so that detection can be made with X-ray detectors but wafers would be

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more expensive to manufacture.

3.2.2.3 Direct Writing on the Wafer

All techniques analyzed in previous pages were using a mask to transfer the circuit layout on the silicate substrate. A new technique, the electron-beam, permits one to write the circuit layout directly on the wafer. (See Figure 6, page 35).

In principle, direct writing with the electron-beam would be essentially the same as mask fabrication by electron-beam except that writing would be directly on a photoresist sensitive to electrons instead of a mask substrate.

The main disadvantage of this technique is its speed. With X-rays, the whole wafer is exposed in one step but the electron-beam can write just one submicronic point at a time. Output is only 10 wafers per hour with a machine costing $50,000. (7)

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(7) G.D. O'Clock and R.J. Herickhoff. Op.cit., p. 116

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The principal advantage of direct writing is that it provides high resolution without any intermediate steps. With the patterns of the successive layers of the chip stored in a computer memory, it would be fairly easy to precisely align the pattern of each layer with the layers already on the wafer. This feature is of prime importance as it has been shown in previous sections that precise alignment is fundamental at VLSI levels. Another plus of the technique is its ability to compensate for surface defects on the wafer as it can be used like a conventional scanning electron microscope to read the wafer surface as well as to write on it. In such a case, the low speed of the technique would be compensated by much higher yields of fault-free circuits.

3.3 Fabrication and Testing of Circuit Elements

The aim of all previous lithography steps was just to permit the selective deposition of a layer of material to fabricate the active elements of the circuit. The next steps are to "machine" the layer so that they will take different physical configurations (etching) and to add impurities (dopants) into selected areas of the surface

.../59

of the silicon substrate. The process can be visualized on Figure 9. Each layer addition, each dopant implantation, has to be preceded by a lithographic step.

The simplest technique to add a chosen film layer to the wafer is evaporation. It is usually the process chosen to add an aluminum layer before drawing electrical interconnections. In an evacuated enclosure, aluminum is heated by direct bombardment with high-energy electrons and the aluminum vapour thus generated condenses on the cooler wafer forming a very thin film.

Another technique is chemical-vapor deposition (CVD) where the wafer is heated in a dilute atmosphere of gas. Where silane (SiH4) gas is heated, it decomposes into silicon to form a polysilicon layer. In presence of carbon dioxide, it forms a silicon dioxide film and a silicon nitride layer in presence of ammonia. The advantage of this technique is greater thickness uniformities and higher throughput. These advantages are obtained at a greater cost. Systems costs range from $150,000 to $300,000. (8)

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(8) G.C. O'Clock and R.J. Herickhoff. Op.Cit., p. 116

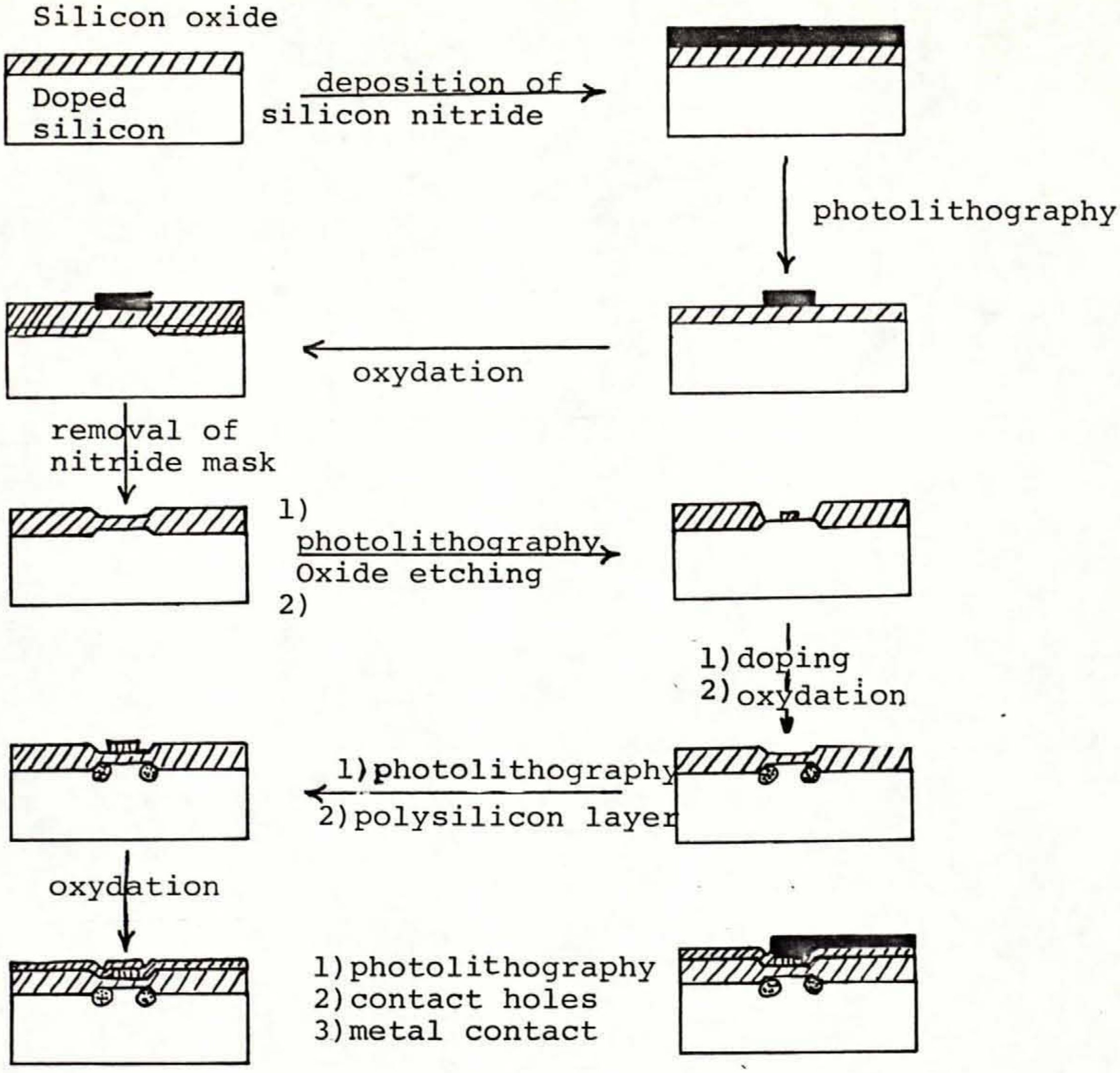

Figure 9: MOS technological process

(Jean-Louis Lardy, "La micro-électronique à très grande intégration", La Recherche, novembre 1980, p. 1248-1256)

Finally, experiments are being conducted on an advanced technique, molecular-beam epitaxy, which is an ultra high-vacuum-evaporation process. Costs of a system range from $250,000 to $550,000. (9) The throughput is somewhat limited, but thickness uniformities are high and thicknesses down to the atomic level are achievable.

In the past, layers were etched by wet techniques. Photoresist was etched by different solvents, silicon oxide by hydrofluoric acid and aluminum contacts by a solution of phosphoric acid. The resolution of wet techniques is not sufficient because the surface tension causes the solution to bridge the space between the photoresist thereby preventing etching of the underlying surface.

The simple wet techniques are being replaced by higher resolution yielding plasma etching where a suitable gas, excited at high frequency, breaks down into elementary parts and attacks the layer to be "machined".

As an example, when freon is excited by a high-frequency electric discharge at very low pressure, it

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(9) G.C. O'Clock and R.J. Herickhoff. Op. Cit., p. 116

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breaks down into a variety of ions (molecule or part of a molecule having gained or lost one or more electrons) and radicals (neutral molecule or part of a molecule having a lone reactive electron). These free atomic fluorine radicals diffuse through the perforated aluminum shield which protects the wafer from the electric discharge and attacks the polycrystalline silicon (where it is unprotected by photoresist) to form a volatile reaction product which is evacuated through the vacuum system.

Plasma-etching provides better control over the edges of the etched surface and it reduces risks of contamination. It will be the technique used for VLSI.

Plasma systems range in price from $50,000 to $170,000 and their throughput is 20-60 wafers per hour. (10)

A semiconductor is a non-conductive material which has been doped by some selected impurities.

The classic doping technique is the selective diffusion of impurities into the silicon substrate via windows drawn in the silicon oxide masking layer. Temperature determines the solubility of the impurities in the silicon, so that

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(10) Ibid., p. 116

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the temperature of the oven is adjusted to control the amount of impurities introduced into the substrate.

A newer technique, ion implantation, which is more complex and costly, permits doping at room temperature. The dopant atoms are ionized, mass-separated in a magnetic field and accelerated to high energy when they pass through a potential difference. At the end of their flight, they enter into the wafer to a depth determined by their mass and energy. The main advantage of the technique is its potential to introduce a wide variety of atomic species and to precisely control their concentration.

Another advantage would be the possibility of introducing impurities through the gate oxide thus permitting tuning of the threshold voltage of MOS transistors. On the other hand, when the accelerated ions enter into the silicon crystal, they damage the lattice so that moderate temperature annealing is necessary to restore the lattice to its original state.

It should be noted that this equipment costs around a quarter to half a million dollars. (11)

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(11) G.D. O'Clock and R.J. Herickhoff. Op. Cit., p. 117

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The classical way of testing the circuits before cutting them from the wafer is with a computer-controlled testing machine which positions itself over each chip, makes contact with the circuit through a few dozen very fine needles, tests the circuit and marks it with ink if it is defective.

Testing of VLSI chips will be a major problem. The number of devices on the chip increases as the square of the linear dimensions of the chip but the number of input/output pins increases only linearly. In other words, it is very difficult to detect a faulty transistor in a circuit containing 100,000 of them when there are just a few dozen input/output pins to address them.

A possible solution would be to devote a percentage of the chip to carry out self-testing.

Another solution proposed has been to build redundancy or "spare parts" in the chip. In such a chip, faulty cells are destroyed by burning fuses during testing so that the circuit is re-routed to one of the spare fault-free cells. Because such testing and "repair" would increase cost, it is not yet certain if this technique will be adopted.

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3.4 Conclusion

Computer-Aided Design will become a major necessity for the design of VLSI chips but additional research will have to be done in fields such as design automation, verification algorithms and new circuit architectures.

As international borders seem to be closing to the free flow of CAD programs developed in universities, it becomes important to develop Canadian capabilities in this important field.

In the fabrication of VLSI chips, the major challenge will be in lithographic processes to reduce line width and to improve yields of fault-free circuits. Testing of finished circuits will be a major problem at the VLSI level, but solutions are already being explored by the concerned manufacturers.

The evolution of VLSI will be accompanied by a dramatic increase in the level of investments necessary to produce state-of-the-art integrated circuits. The complex equipment required to manufacture VLSI circuits means that operator skills will need to be higher and maintenance and repair will be more costly.

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This chapter described the state-of-the-art in VLSI technology. Future circuits will use optical gates (electricity being replaced by light) or biochemical gates. In the meantime, R&D will be focused on concepts such as three-dimensional circuits and systems-on-a-wafer (many different circuits interconnected on a single wafer).

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OVERVIEW OF THE INDUSTRY

1.0 International Perspective

As demonstrated by Figure 10, the United States is the major producer of integrated-circuits: $2.4 billion in 1978 as opposed to $1.1 billion for Japan and $0.6 billion for the EEC. When Canada is compared to the different EEC countries, (see Figure 11) it fares poorly. A possible explanation is that the three Canadian producers, Mitel, Bell-Northern and Linear Technology manufacture a high percentage of their circuits for internal use.

Technically, the United States is said to lead in microprocessors while Japan is renowned for memories. The end-products incorporating these chips are also different for both countries. American applications are mainly in fields related to computers while their Japanese counterparts are consumer products. It must be added that Japan is now planning to take the lead in computers.

Marketing factors also differ appreciably in each of these markets. In the United States, price is the most important factor followed by quality and terms of delivery. In the European market, these last two factors are judged as

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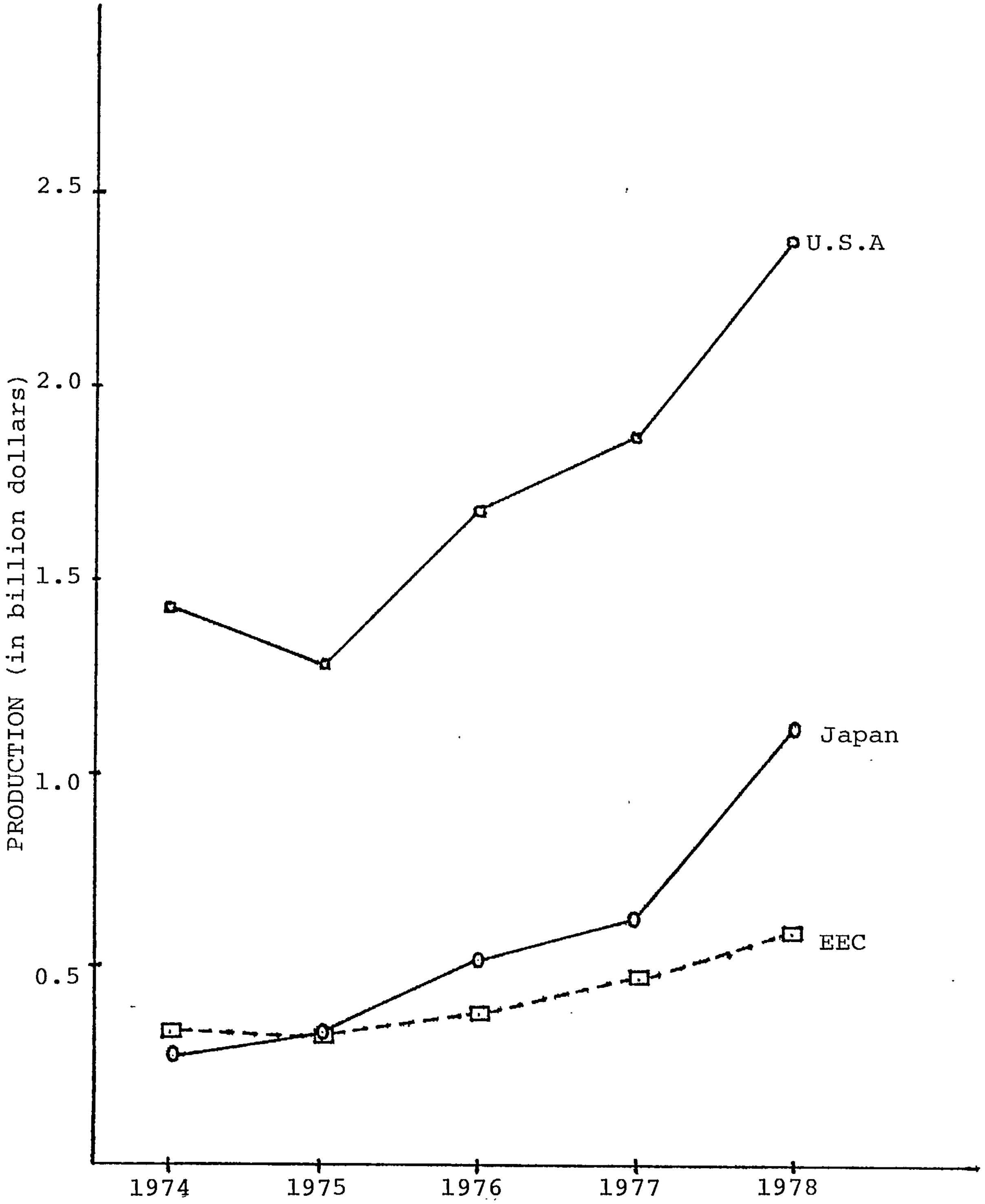

Figure 10. World production of integrated circuits.
(Source: Competitive Factors Influencing World Trade in Integrated Circuits. United States International Trade Commission, 1979.)

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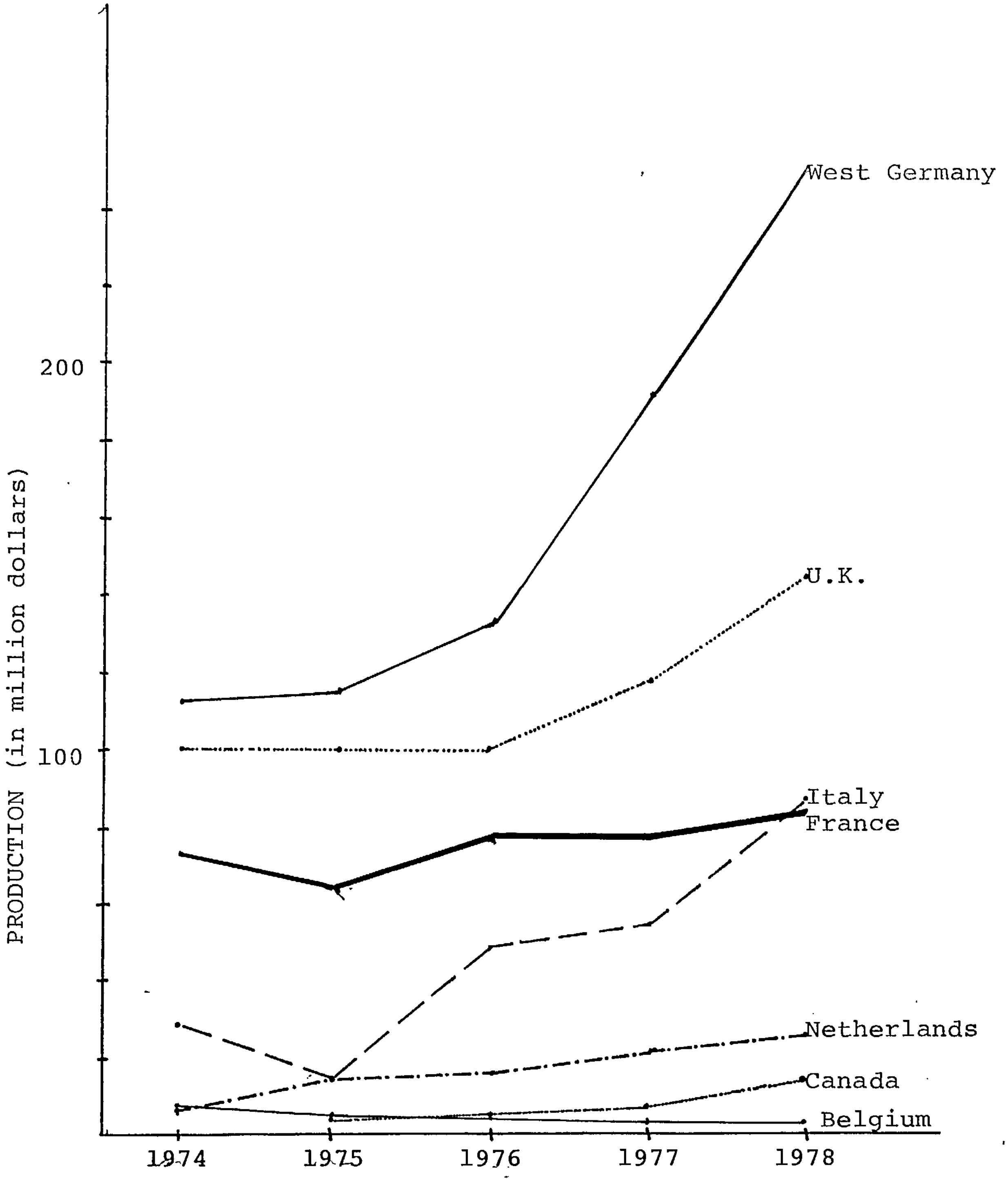

Figure 11. Production of Integrated Circuits for EEC Countries and Canada. (Source: Competitive Factors Influencing World Trade in Integrated Circuits and January issues of Canadian Electronics Engineering, 1978,1979,1980)

Note: Canadian figures are shipments in Canadian dollars.

most important, price being ranked last. In Japan, quality is the overwhelming factor. (12)

The international flow of integrated circuits is as follows: Japan exports mostly to Asian countries (although recent trends indicate a certain penetration of U.S. and EEC markets) and the United States exports mostly to the EEC members. (13)

2.0 The IC Industry

Presently, the integrated circuit industry is dominated by a handful of companies like Intel, Zilog, Motorola and Rockwell in micro-processors, and Fairchild, Fujitsu, Hitachi, Intel, Mostek, Texas Instruments in memories. (Table II)

The IC industry is one of the most dynamic. A state-of-the-art product has a product life of 2-4 years at the most. The name of the game in microelectronics is to develop a standard part so advanced as to become a *de facto* industry standard and to sell it by the millions because this industry

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(12) *Competitive Factors Influencing World Trade in Integrated Circuits*, p. 24.

(13) Ibid, p. 53.

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United States	Japan	EEC
IBM Texas Instruments National Semiconductor Motorola Intel Fairchild	Nippon Electric Hitachi Toshiba Fujitsu Matsushita Sharp	Philips Siemens L.M. Ericson Inmos Eurotechnique Compagnie générale d'électricité
Signetics Mostek AMD RCA Harris Zilog Rockwell	Mitsubishi Tokyo Sanyo Oki Sony Fuji	Thomson-CSF General Electric SGS-ATES Harris-Matra

Table II: Producers of Integrated Circuits

is very volume-sensitive - a doubling of volume reduces costs by 20 to 30 percent.

A consequence of this rapid growth is that prices (and profits) decrease quickly for a given product (see Figure 12). Old products "do not contribute to fund the R&D necessary to renew the technology that permits the innovative advantage in costs and pricing". (14) New products mean high profit and high volumes.

This explains the very high expenditures on R&D. World expenditures were $329.8 million in 1974 and $529.6 million

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(14) Ibid., p. 22.

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in 1978. These figures correspond to 16% and 13% of the world shipments for these respective years. (15)

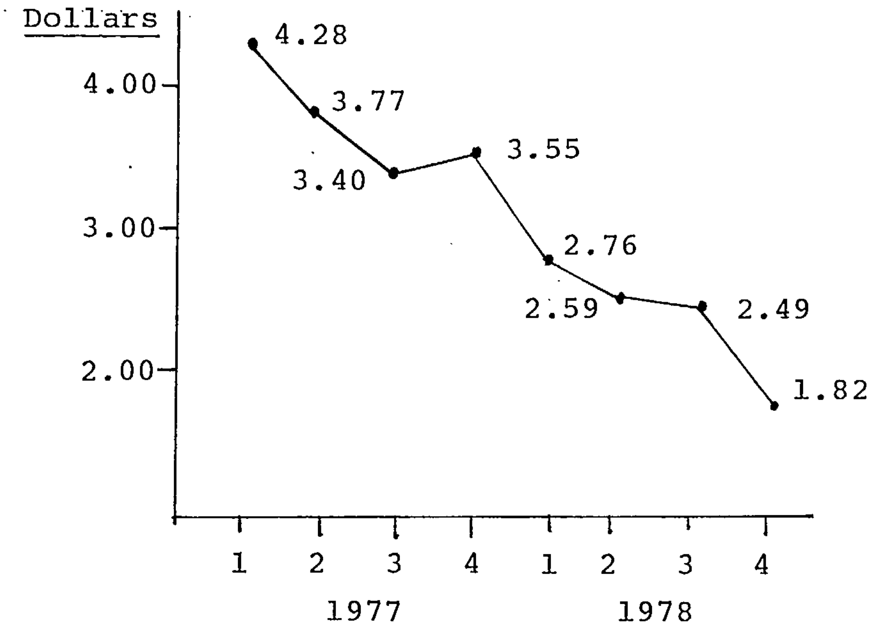

Figure 12: Average Unit Prices of 4K RAMs
(Source: Competitive Factors Influencing World Trade in Integrated Circuits, p. 20)

This rapid technological change also means that investments are enormous. To build a manufacturing facility for the fabrication of VLSI chips, some $90 million is required. The technology is growing at such a rate that the economic life of the expensive equipment is 3 years on the average

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(15) Compiled from data published in Competitive Factors Influencing World Trade in Integrated Circuits, p. 20

because it constantly has to be replaced by more advanced equipment. This is why fast depreciation on equipment is most important.

Investments in plants and production equipment were, respectively for 1974 and 1978, $544 million (38% of shipments) and $897 million (38%) for the United States and $41 million (6.8%) and $172 million (10.7%) for Japan. The figures for Japan are quite surprising when considered with the fast growth of the Japanese industry. One explanation would be differences in reporting these statistics.

It has been predicted by Gnostic Concepts Inc. (a California data company which tracks the industry) that U.S. companies will have to invest some $9 billion by 1988 for facilities, equipment and R&D. (16)

Technological innovation alone does not suffice to explain investments of this order of magnitude. Another reason is that the market for integrated circuits is literally exploding; world sales should pass from some $5 billion in 1978 to around $30 billion by 1988 and reach an impressive

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(16) G. Bylinsky. "The Japanese Chip Challenge". Fortune, March 23, 1981, p. 115-122.

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$100 billion toward the end of the century. (17) The fastest growth will be in sales of micro-processors. The Dutch Advisory Group on the Social Effects of Microelectronics forecast a more than twelve-fold increase in sales of micro-processors from 1978 to 1990. (18)

One surprising consequence of the investments figures in R&D and in advanced equipment is that productivity has been somewhat stagnant in the United States as opposed to Japan (see Figure 13).

A note of explanation has to be given for productivity. These figures do not take into account that many more transistors were engraved on the chip of 1978 than on the chip of 1974 - the product-mix of each year is different.

The IC industry is also characterized by the vertical integration of firms. More than one-half of the U.S. production is sent to other branches of the same company. This way, the R&D is less risky since it is done for a precise product. Also, demand for the chip is certain and there is better

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(17) G. Bylinksy, Op. Cit.

(18) Report of the Advisory Group on Microelectronics, p. 61.

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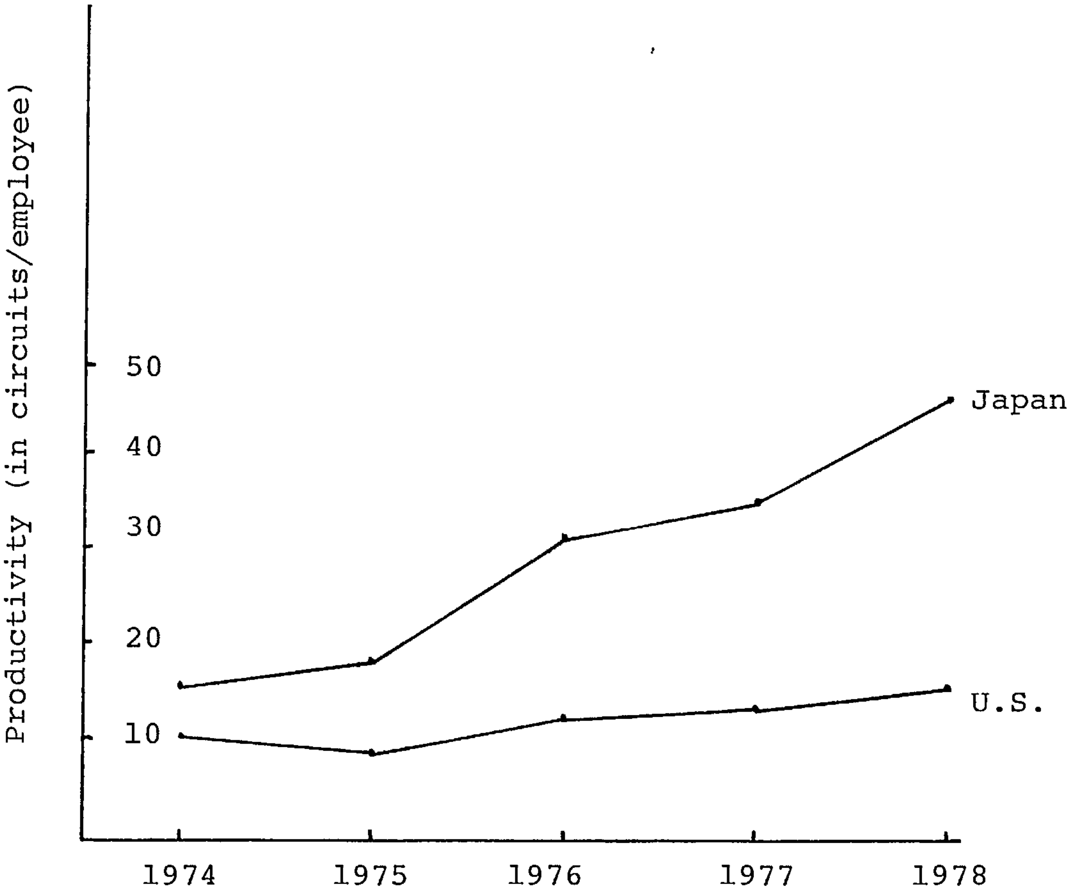

Figure 13. <u>Productivity of the IC industry</u>
(Source: compiled from data published in
<u>Competitive Factors Influencing World</u>
<u>Trade in Integrated Circuits</u>).

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co-ordination between the design of the chip and the final product.

Finally, analysts of the microelectronics industry usually forecast some staffing problems. In fact, just a few universities offer courses in integrated circuit technology (usually at the graduate level) and companies must usually rely on on-the-job training which is not always attractive because specialists can work just a few weeks or months before being offered a better job by competitors.

Universities and technology schools cannot graduate students fast enough. Experienced electronic engineers and technicians are in short supply. In fact, Mitel estimates that it would need 2000 new engineers for the next four years while Canadian universities will graduate just some 1400. In the Ottawa-Carleton area, 320% more electronic assemblers and 250% more electronic technicians, technologists and engineers will be employed in 1985 than today. (19) These figures are contradicted by historical data for the United States and Japan. An explanation may be that the above figures also refer to the production of a final product rather than just ICs.

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(19) Microelectronics 1980. A survey of High Technology Companies in the Regional Municipality of Ottawa-Carleton, p. 10.

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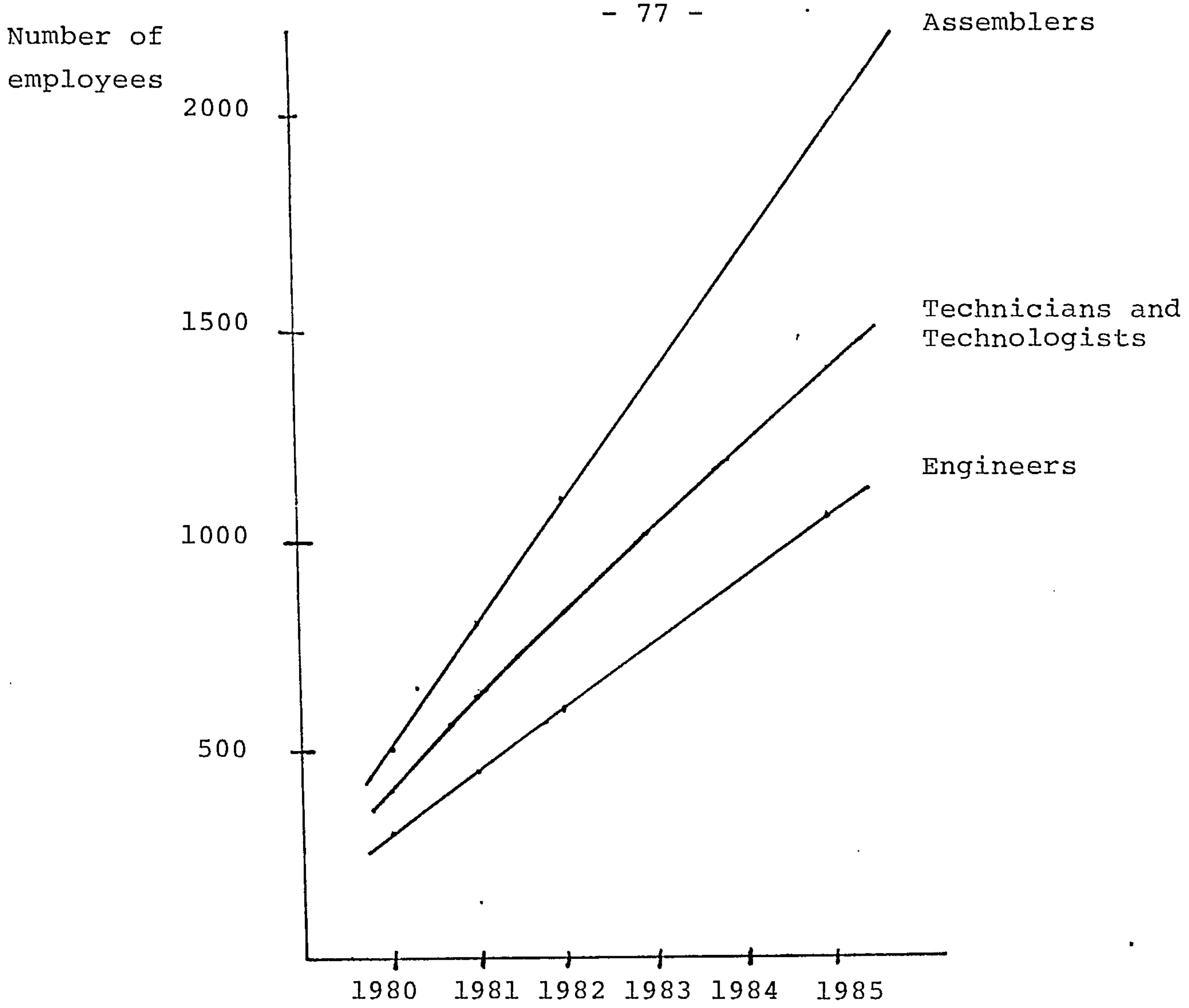

Figure 14 Employment in Microelectronics in the Ottawa-Carleton Area .

Source: Microelectronics 1980, A Survey of High Technology Companies in the Regional Municipality of Ottawa-Carleton.
(Ministry of Industry and Tourism-Ontario)

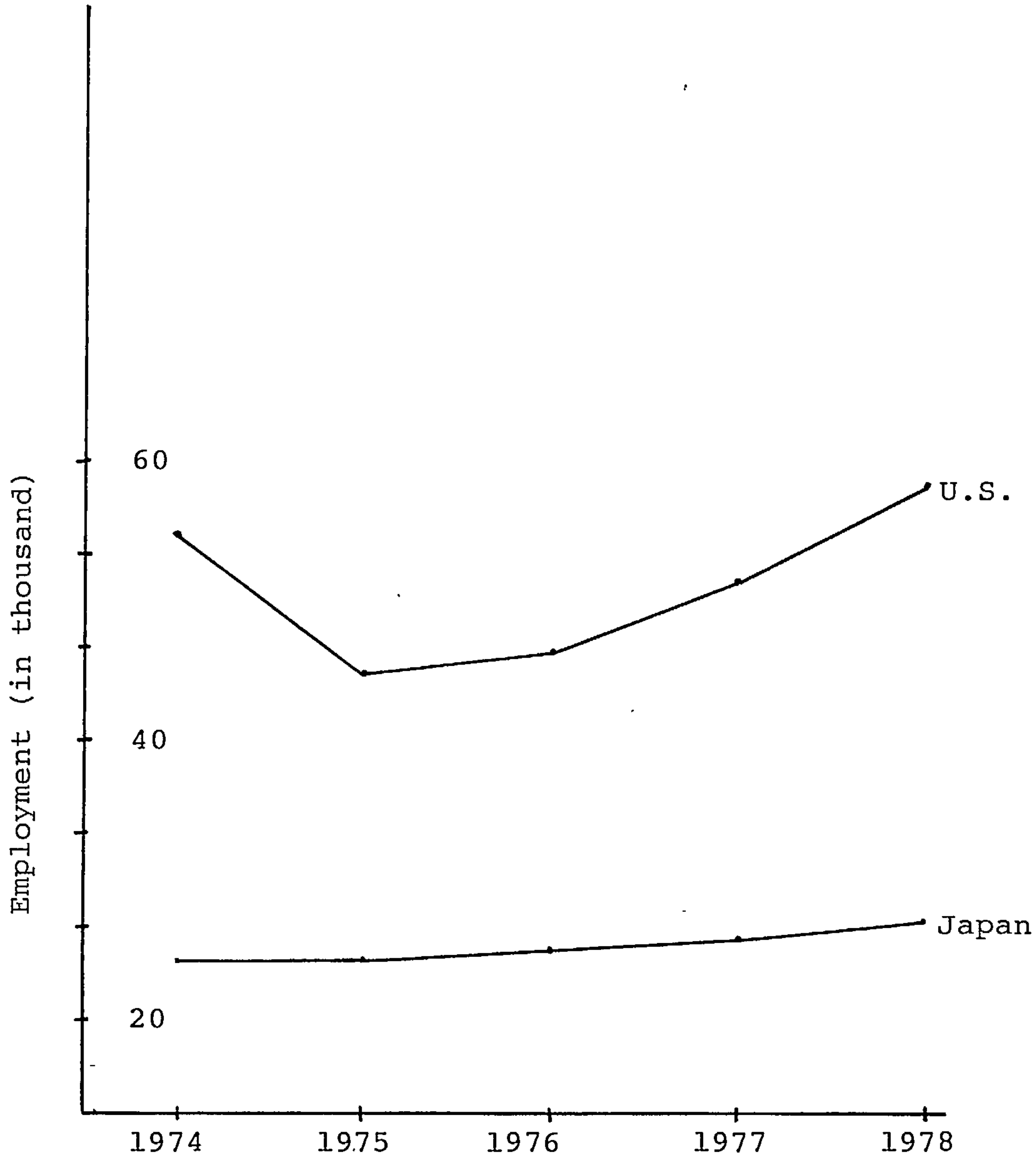

Figure 15. Employment in the fabrication of integrated circuits. (Compiled from data published in Competitive Factors Influencing World Trade in Integrated Circuits)

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This overview of the integrated circuit industry would not be complete without a few words on governmental involvement. Although data specific to the fabrication of integrated circuits has not been compiled, it is interesting to note that other governments are pouring large sums of money into microelectronics programs - over $1 billion in the U.S.A. and Japan each, $ 700 million in United Kingdom, France and Italy each, compared to $ 50 million in Canada (see Figure 16). West Germany is planning to invest $ 25 million per year into R&D to fabricate a state-of-the-art integrated circuit and France has similar plans with Eurotechnique Britain is establishing a complete integrated circuit manufacturing company, Inmos, with an investment of $120 million. This company is expected to make 64K random-access memories (RAM). In Canada, Mitel has been awarded $ 21 million to expand its LSI (VLSI) facility in Bromont. This is the only Canadian commitment to fabrication of chips up to now.

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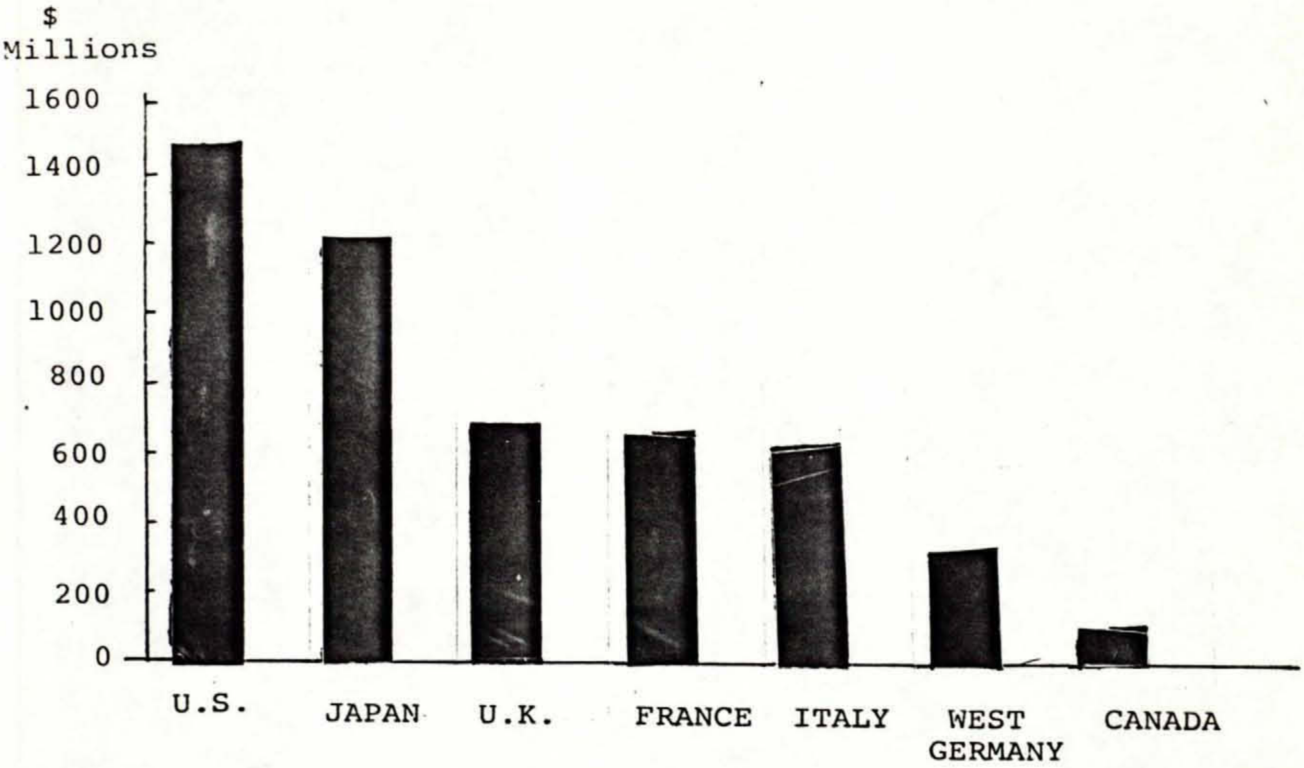

Figure 16. Government Sponsored Programs in Microelectronics.

Source: Microelectronics: Canada at the Crossroads. Conference given by Mr. K. Revill to the Interdepartmental Committee on Futures Research, Ottawa, The 5th of December 1980.

OVERVIEW OF CANADIAN TECHNOLOGICAL EXPERTISE

One has just to consider the success of a company like Northern-Telecom and its semi-conductor components group to realize that Canada has nothing to envy from any other country in microelectronics.

Most Canadian expertise is in MOS (Metal-Oxide-Semiconductor)*; presently, the most widely used technology. In at least one technology, Canada is recognized as a world leader; ISO-CMOS technology (Mitel). It uses silicon oxide to isolate the p and n channel of transistors in order to boost speed. In fact, it permits MOS to rival bipolar technology in term of speed.

Canadian universities offer a wide range of expertise in chips manufacturing and design (Toronto, Waterloo, Sherbrooke), in computer aided design (Carleton), in analog/digital hybrid circuits for communications (Toronto) and in universal logic arrays (Sherbrooke and Toronto). In fact, researchers from the University of Sherbrooke were instrumental in the development of the Quebec-chip (a LSI chip) by Mitel and they are presently designing the first Canadian VLSI chip: 100,000 transistors. A word of caution should be added. With the cost of equipment

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* This technology has been described in a previous report published by MOSST, Microelectronics (1980).

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sometimes prohibitive, universities generally do not have access to the latest equipment.

This situation might change with the recent announcement, by the Minister of Industry, Trade and Commerce, of the establishment of ten Centres of Advanced Technology in Industrial Applications of Microelectronics, one located in each province. These centres will be located at major Canadian centres in the University of Toronto, the University of Sherbrooke, the University of Manitoba, the University of Alberta, and the University of British Columbia. The other centres will be announced in the near future. Each centre will receive $ 1 million over the next five years. It is hoped that these centres will encourage Canadian industries in all sectors to apply the new technology and that they will contribute to the Canadian manufacture of microelectronic devices.

Another initiative, from the private sector, is the creation by Bell-Northern, of an assistance program to universities. Under this program, universities submit computer tapes of student designs and the company manufactures a few samples of these chips.

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Even though the Canadian expertise base is much smaller than in Japan or the United States, its contribution to this fast developing technology has been surprisingly lively. For example, Mitel is designing the first Canadian-made microprocessor, similar to Motorola's 6802.

In addition to Northern-Telecom, Mitel and Microtel Pacific Research who design their own circuits, there are just three design houses in Canada: CAD/CAM Graphic Systems, Mosaid and Siltronics.

CAD/CAM Graphic System is oriented more toward general CAD than circuit design. Mosaid is the most widely known of the three. It specializes in the analysis of dynamic RAM and in its own designs. Siltronics custom designs bipolar circuits (at the LSI level and down) to be fabricated in the United States.

A survey of Canadian manufacturers of LSI circuits can be made very rapidly. Canada has just three major manufacturers: Mitel, Northern-Telecom and Microtel Pacific Research. (Linear Technology might eventually upgrade its low scale integration facilities to LSI or VLSI). Other manufacturers are Anateck Electronics (B.C.) (Hybrid circuits for telecommunications), Pacific Microcircuits (B.C.) (Design and prototyping in custom

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ICs) and Optotek (Ottawa) (Gallium arsenide).

Canadian manufacturers have equipment of a level of sophistication approximately equivalent to world industry standards in the areas of mask projection, chemical vapor deposition, plasma etching and ion implantation equipment. Mitel is even planning to purchase an electron beam. A weak area is that of mask generation. Mitel has its masks made in the U.S.A. and Northern Telecom uses optical generators rather than lasers.

The largest Canadian producer of chips is the microelectronics factory of Northern-Telecom at Corkstown near Ottawa which is said to be one of the best in North America. Their good circuit yield per wafer is superior to the industry average. They were the first Canadians to move to 4 inch wafers. Even though they are among the 10 largest users of semi-conductors in the world, they produce nearly a third of the semi-conductors used in their products and they want to spare up to 20% of their fabrication capacity for other companies.

Mitel designs and manufactures its own chips, of both general purpose and custom telecommunication types, at its Bromont (Quebec) plant. About two-third of these semi-conductor products are sold to other electronic equipment manufacturers in Canada, the United States and the world.

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To conclude, the chips supplied domestically are almost completely limited to specialized telecommunication chips. If microelectronics is taking off as predicted, the Canadian production of chips will be able to supply only a negligible percentage of domestic requirements.

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OPTIONS

In designing any integrated circuit strategy, two questions have to be addressed:

a) should integrated circuits be manufactured domestically or should they be imported?

b) if they are to be manufactured at home, should the whole product line be considered or just a few categories?

This part of the report will not provide answers to these questions but it should provide a better understanding of the issues involved.

1.0 Microprocessors

It has been shown at the beginning of this report that micro-processors are a kind of universal device which can be tailored to specific uses by adding the appropriate programmed instructions.

Experts predict that micro-processors will invade every aspects of our daily lives before the end of the century. In fact, sales of micro-processors will increase twelve-fold over

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the decade.

It can take years to develop a micro-processor so it has to be sold by the millions to recover development costs. This is the reason why the industry is dominated by just a few giants like Intel and Motorola.

Mitel is currently developing its own micro-processor which should be similar to Motorola's 6802. This is accomplished essentially by reverse-engineering. It is doubtful that Mitel's production could satisfy Canadian requirements for micro-processors as most of its production will be for internal use. On the other hand, this initiative will hopefully contribute to keep Canadian expertise up-to-date in addition to being a source of national pride.

Mosaid is also considering the possibility of establishing a microprocessor manufacturing plant.

To succeed in this field, a company would have to have access to the world market because domestic demand may not be large enough.

2.0 Random Access Memories

Random access memories (RAMs) are relatively simple devices because they are made of regular cells repeated one

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after the other so they can be designed by a single person. The computer industry has an insatiable thirst for these devices. Sales of 64K RAMs should increase from $ 2 million in 1980 to $ 2 billion in 1986 according to Mosaid Inc.(20) The global RAM market could total $ 24 billion before 1990.(21)

This market looks very promising, but it is the microelectronics sector which changes the most rapidly. As soon as technology proceeds to the next integration level, it will first be applied to RAMs. Once a company is committed to the RAM business, it has to go to the next integration level or quit the market. There is no middle ground. 64K RAMs started recently to be commercially available and 256K RAMs are expected to appear on the market by 1985.

64K RAMs are offered or will be offered, by American companies (Texas Instruments, National Semiconductors, Intel, Fairchild, Mostek), by Japanese companies (NEC, Hitachi, Fujitsu, Toshiba), by one French company (Euro-technique), one British company (Inmos) and by one German company (Siemens). Mosaid Inc. forecast that the market will be dominated by no more than five large corporations in 1990.

Investments in RAM are huge, the technology is constan-

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(20) G. Bylinsky. Op. cit.

(21) VLSI MOS RAM Market - Status and Future. Mosaid Inc. Ottawa, 1980, p. 8

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tly changing and producers are firmly established. The cards have already been suffled and dealt. This option would represent a large risk.

3.0 Custom and Semi-Custom Circuits

Custom circuits are already widely used in devices such as ROMs* to instruct micro-processors in appliances, in cars and in communications equipment.

More and more customers are attracted by custom chips because a fine design can give a company's products unique features and a proprietary design as opposed to micro-processors.

Dataquest predicts that the combined markets for custom and semi-custom circuits could grow from $725 million in 1981 to $ 3 billion in 1985, one sixth being in semi-custom chips.(22) In fact, the custom chips market accounts for less than 10% of today's market for integrated circuits, but this percentage could well become 50% by 1990.(23)

In the past, custom circuits were restricted to cases where the producer could foresee a large production run because the design and the production of such circuit was a long and costly business.

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* ROM (Read Only Memories)

(22) Semi-Customised Chips. The Economist, April 24, 1982, p. 114

(23) P. Mattera. The Boom in Tailor-Made Chips. Fortune, March 9, 1981, p. 122

A new technology, universal logic arrays (ULA), could greatly reduce the importance of these problems. These chips contain regular arrays of hundreds or thousands of isolated logic gates previously made from a master slide. A logic designer specifies how the gates are to be interconnected on the chip to optimize the circuit for a particular application. (A library of standard functions can be used). A mask is then generated and the final metallization step is done.

The disadvantage of ULAs is that they do not use all the cells; there is some waste. It could be replied that with VLSI, some waste can be afforded in most applications. Also, this technology would require a strong collaboration between customers and manufacturers, though the latter might be reluctant to share a great deal of confidential technical information and product plans.

The Quebec-chip of Mitel is a ULA containing 1,500 gates and 60,000 transistors. Their next ULA will be a VLSI chip with 100,000 transistors.

A new chip of this type can be produced in a matter of weeks rather than months since interconnection masks can be drawn very rapidly using computer-aided-design (CAD). As an example, Mitel developed a circuit for the Department of Communications in approximatively 4 months at a cost of $ 13,000 using this technique while a similar circuit was developed elsewhere in some 15 months at a cost of $ 120,000

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using conventional techniques.

A few large manufacturers are devoting part of their production to custom circuits: Motorola, Fujitsu, Fairchild, Signetics, National Semiconductors, Ferranti (U.K.). A large number of small companies are entering the market: LSI Logic, ZyMos, VLSI Technology, Applied Micro-Circuits, American Micro-Systems, International Micro-Circuits, California Devices, Interdesign and Silicon Systems.

Universal logic arrays could represent a technological opportunity for Canada since the whole field is fairly new and Canada has strong expertise in this area. In addition, by doing the last metallization at home, huge savings could be achieved; if all previous steps cost $1, then the last metallization costs $2 and final tests cost $4.

This option could represent a good business opportunity for the two Canadian chips manufacturers, Mitel and Northern Telecom. Also, the Centres of Advanced Technology in Industrial Applications of Microelectronics could provide the link between users and makers and could eventually manufacture those chips. However, further analytical studies should be done to assess the viability of this option.

Another technology in custom circuits is being presently developed by Carleton University and Mitel. It is a combined CMOS/N-MOS technology for mixed analog/digital applications

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which is particularly appropriate for telecommunication circuits. However, such circuits are presently limited to the LSI level because voltages currently used would "burn" smaller lines. In the future, telecommunication circuits may use lower voltages so that such circuits could be designed at the VLSI level.

Even if semi-custom chips are a promising alternative for Canadian short production runs, fully customized circuits of the kind produced by Northern-Telecom remain a priority for Canada because they are the ones which permitted Canada to become a leader in the field of telecommunications. It is to be expected that both producers of chips (Mitel and Northern-Telecom) will continue to rely heavily on these proprietary chips.

Finally, Canada is at the leading edge of a new technology: gallium arsenide. As indicated on page 32, this technology is particularly useful for telecommunication application. Few companies are involved in this technology (see Table III).

Scientists in the Department of Communications Research Centre have been involved with this material since the sixties. Optotech of Ottawa is developing design and manufacturing methods to produce gallium arsenide circuits from wafers produced by Cominco (Trail, BC) under a contract from Department of Communications and Department of Supply and Services.

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In consideration of the early involvement of Canada in this technology and in consideration of its potential in the field of telecommunications, this area of research should be pursued.

USA	JAPAN	OTHERS
MSC	FUJITSU	PLESSEY
HP	MITSUBISHI	THOMSON CSF
TI	NEC	PHILIPS
AVANTEK	TOSHIBA	
RAYTHEON	KAWAZAKI	
VARIAN		
RCA		
GIGABIT LOGIC		

Table III: Manufacturers of Gallium Arsenide Devices.

4.0 Silicon Foundries

Chips could be designed in Canada and subsequently be manufactured in specialized houses - silicon foundries. On the other hand, it is not certain that these foundries would accept short production run contracts for Canadian companies.

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CONCLUSION

With microelectronics, devices are made much smaller, lighter, cheaper, faster, more reliable and power-efficient as integration levels evolve towards VLSI. Future chips will contain many more functions and the limit to these trends cannot yet be seen.

When the micro-processor was first developed, it was acclaimed as a scientific breakthrough. While no one could foresee any use at that time for such a "toy", it can now be found in every home. History might well repeat itself with VLSI chips. Most analysts feel that the number of applications could be tremendous, but nobody really knows what the full range of these applications will be beyond those outlined in this report.

For the time being, the exact nature of the impact of VLSI on microelectronics applications is difficult to predict with any accuracy. It seems certain that they will be in storage media for computers and word processors, in more powerful micro-processors and applications of VLSI custom chips in communications, as well as in electronic games. In the longer term, VLSI will gradually influence the processing unit of robots to produce a new generation of intelligent robots.

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The design of VLSI chips will constitute a formidable challenge because nothing as conceptually complex has ever been attempted. Because no human being can keep mental track of the details of VLSI designs, computers will be used extensively. In the longer term, an entirely new design approach may be required - large systems design methodology.

As for the fabrication process itself, the major challenge will be in lithographic processes to reduce line width to the sub-micron level while improving the yield of fault-free circuits. Testing of finished circuits may be another problem at the VLSI level, but solutions are already being explored.

The evolution of microelectronics towards VLSI will be accompanied by a dramatic increase in the level of investments necessary to produce state-of-the-art integrated circuits.

Currently, the chips manufactured in Canada are almost totally limited to specialized telecommunication chips. If microelectronics takes off as predicted by most informed analysts, the Canadian production of chips will be able to meet only a negligible percentage of domestic requirements.

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Given the high costs associated with VLSI, the Government should consult with universities, representatives of both industrial manufacturers and users of chips, the National Research Council and concerned federal departments before considering any national policy in VLSI.

APPENDIX I

Tentative List of Canadian Researchers in Semiconductor Technology

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- Gallant, M.
- Hawaway, R.A.
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- Houghton, D.
- Ingrey, S.J.
- Kriegler, R.J.
- Kuhn, M.
- Lee, E.Y.
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- Smith, G.M.
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- Streater, R.W.
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APPENDIX II

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