Directorate of
Intelligence

#233 6 ~~Secret~~

23306

CIASOV 89-10066X

The Soviet Microelectronics Industry: Hitting a Technology Barrier

A Research Paper

large fold-outs

CIA SPECIAL COLLECTIONS
RELEASE AS SANITIZED
2000

~~Secret~~

SOV 89-10066X
SW 89-10032X

August 1989

[illegible]

0167

Warning Notice	Intelligence Sources or Methods Involved (WNINTEL)
National Security Information	Unauthorized Disclosure Subject to Criminal Sanctions

Dissemination Control Abbreviations	NOFORN (NF)	Not releasable to foreign nationals
	NOCONTRACT (NC)	Not releasable to contractors or contractor/consultants
	PROPIN (PR)	Caution—proprietary information involved
	ORCON (OC)	Dissemination and extraction of information controlled by originator
	REL...	This information has been authorized for release to...
	WN	WNINTEL—Intelligence sources or methods involved

A microfiche copy of this document is available from OIR/DLB (482-7177); printed copies from CPAS/IMC (482-5203; or AIM request to userid CPASIMC). Regular receipt of DI reports can be arranged through CPAS/IMC.

Classified [illegible]
Declassify [illegible]
Derived from multiple sources

All material on this page is Unclassified.

Directorate of Intelligence

~~Secret~~

The Soviet Microelectronics Industry: Hitting a Technology Barrier

A Research Paper

This paper was prepared by
, Office of Soviet Analysis;
Office of Science and Weapons
Research; and
, with contributions from
SOVA, and , OSWR

Comments and queries are welcome and may be
directed to
SOVA.

Reverse Blank

The Soviet Microelectronics Industry: Hitting a Technology Barrie

Summary

Information available as of 19 June 1989 was used in this report.

The USSR has an acute shortage of very-large-scale integrated (VLSI) circuits. These integrated circuits are necessary to meet the challenges posed by General Secretary Gorbachev's industrial modernization plans and will be critical to a number of advanced weapon systems the Soviets are developing for deployment in the 1990s. The manufacture of VLSI devices requires levels of precision, complexity, cleanliness, and miniaturization that the Soviets have not yet been able to reach in the industry at large. Although they achieved full-volume production of first-generation VLSI chips (64K memories) in 1984, device yields remain well under 10 percent (compared with device yields of over 85 percent in US plants) and reliability is a problem. While the USSR has a dearth of 64K chips, the West is manufacturing second-generation VLSI devices (that is 256K and 1-megabit memories) in volume

Second-generation VLSI chips present the Soviets with formidable manufacturing challenges. Full-scale production requires more sophisticated manufacturing equipment than that used for less advanced ICs. The Soviets probably have reached a technology barrier at the second-generation VLSI level; to produce these devices in volume, they will have to acquire or produce substantial amounts of advanced manufacturing equipment to retool many of their IC production plants

The Soviets have several options for acquiring the technology necessary to retool their microelectronics industry:

- Accelerating domestic development and production programs.
- Coordinating research and production efforts with East European members of the Council for Mutual Economic Assistance (CEMA).
- Acquiring Western technology, possibly in part through joint-venture efforts with Western companies

The preferred solution from the Soviets' perspective is to reequip the microelectronics industry with indigenous production equipment. Yet, despite a large industrial infrastructure to support the development and production of microelectronics manufacturing equipment, the Soviets thus far have been unable to manufacture high-quality equipment in volume. [redacted] depict a microelectronics equipment sector that turns out poor-quality products because of resource and labor problems and a relatively antiquated production environment

[redacted] analysis of commercial Soviet ICs produced at the medium- and large-scale levels of integration confirms the [redacted] assessment of the poor quality of indigenously produced equipment. This analysis indicates a number of equipment deficiencies that suggest manufacturing problems at the VLSI level of production will be even more serious. Consequently, we doubt that the Soviets in the 1990s will be able to produce equipment capable of manufacturing ICs that match the complexity or performance levels of Western devices. Soviet leading-edge production technology probably will continue to lag that of the West by one to two IC generations.

To supplement indigenous efforts, the Soviets will continue to pursue cooperation with the East European member countries of CEMA. Within CEMA, the USSR can gain most through increased cooperation with East Germany. The East German combine Carl Zeiss Jena is Eastern Europe's leading producer of microelectronics manufacturing equipment, and it ships approximately 80 percent of its output to other CEMA countries, chiefly the USSR. East Germany's success in acquiring critical [redacted] IC production equipment and technology and its resulting success in 1988 of achieving pilot production of second-generation VLSI devices illustrates the type of access to East European and Western technology the Soviets hope to acquire through their CEMA relationships. Soviet benefits from CEMA cooperation probably will be limited, however, by the desires of the East European member countries to develop high-technology industries to support their own objectives

To compensate for CEMA's inability to produce high-quality microelectronics manufacturing equipment in volume, the Soviets will continue to place great emphasis on acquiring Western machinery. We believe that, since the early 1970s, the Soviets through both legal, licensed purchases and illicit acquisition programs have acquired enough IC manufacturing equipment from the West to outfit up to a third of their IC production lines. Reequipping their industry to support the production of second-generation VLSI devices could require a similar level of Western acquisitions in the 1990s

The USSR will continue to exploit any weakness in Western export controls and may attempt to build a constituency in the West that favors relaxing the COCOM regulations governing advanced microelectronics technology. The Soviets may turn increasingly to joint ventures with Western firms to obtain microelectronics manufacturing technology and know-how and, in some cases, to facilitate the production and marketing in the West of Soviet-designed manufacturing equipmen

Contents

	Page
Summary	iii
Preface	ix
A Struggling Industry	1
Microelectronics Manufacturing Equipment: The Industrial Base	3
The Technology Level of Equipment Used in Soviet Plants	5
Past Efforts To Reequip the Production Base	19
Domestic Equipment Industry	19
CEMA Cooperative Efforts	20
Acquisition of Equipment From the West	21
Plant Modernization Requirements for the 1990s	28
Soviet Options for Reequipping the Microelectronics Industry	29
Accelerating Domestic Production	29
Maintaining Pressure Within CEMA	30
Continued Dependence on the West	30

Appendixes

A.	Growing Soviet Demand for Advanced ICs	33
B-1.	Microelectronics Equipment Design Bureaus	37
B-2.	Microelectronics Equipment Production Plants	39
C.	Microelectronics Production: Sand to Circuits	41

Preface

The Soviets are having trouble producing ICs at the VLSI level, in large measure because of inadequate supplies of advanced manufacturing equipment. This paper addresses the nature of the Soviets' equipment shortfall, analyzes the reasons for the shortfall, and assesses Soviet options for overcoming i[redacted]

We have conducted a thorough analysis of all reporting on Soviet microelectronics manufacturing equipment. We have information on the range of equipment produced in the Soviet Union and the quality and technology level of Soviet equipment compared with that produced in the West. We are also able to tie specific products to key microelectronics equipment design bureaus and production plant.

We are faced with major information gaps, however, on the supply, composition, and application of Soviet microelectronics manufacturing equipment and on the organizational dynamics of the sector of the microelectronics industry that produces this equipment [redacted] has long been biased in favor of microelectronics device production instead of production of the equipment that manufactures those devices. In addition, most reporting on production equipment is fragmentary, descriptive, and inadequate for rigorous analysis of Soviet equipment production capabilities or retooling requirements

Because of these large information gaps, we have had to come to grips indirectly with the nature of the Soviets' manufacturing equipment shortfall, as well as the possible reasons for the shortfall. To that end we:

- Analyzed a variety of Soviet ICs—including advanced devices—to determine the types and quality of equipment the Soviets used to manufacture them.
- Examined Soviet–East European cooperative programs in the field of IC production equipment to identify areas where the Soviets are attempting to supplement their indigenous capabilities and their program for acquiring Western equipment.
- Reviewed the Soviets' technology transfer program to identify trends in the types and quantity of Western equipment they have acquired over time and to gauge the progress they have made in overcoming areas of technological deficiency.

Microelectronics Jargon

A semiconductor *is an element whose electrical conductivity is less than that of a conductor, such as copper, and greater than that of an insulator, such as glass.*

A transistor *is a semiconductor device that acts primarily as either an amplifier or a switch.*

A wafer *is a thin disk of semiconductor material on which many integrated circuits are fabricated at one time. The circuits are subsequently separated and packaged individually.*

An integrated circuit *(IC) is a semiconductor circuit combining many electronic components such as transistors in a single substrate, usually silicon. An IC is commonly called a chip.*

A memory *IC stores large volumes of information in the form of electrical charges.*

A DRAM *(dynamic random access memory) is a type of IC in which data are stored by means of a periodically refreshed electrical charge. A 256K DRAM, for example, stores approximately 256,000 pieces of information. DRAMs are noted for their speed in storing or retrieving information and their low manufacturing cost.*

A microprocessor *is a single IC on which the arithmetic and control logic of a computer are placed. It is sometimes referred to as a "computer on a chip."*

Minimum feature size *is the width or diameter of the smallest element on an IC and is used as a measure of circuit complexity. Minimum feature sizes vary from 10 microns on small-scale integrated circuits to 1 micron on second-generation very-large-scale integrated circuits. A human hair, by contrast, is 100 microns in diameter.*

Oxidation *is the process of growing an oxide layer on the wafer surface to serve as a substrate for the lithography steps.*

Lithography *is the process of transferring a circuit pattern contained on a mask or stencil to the silicon wafer.*

A mask *is a transparent plate or stencil covered with an array of patterns used in making ICs. The mask is used to expose a portion of a silicon wafer for subsequent processing.*

Etching *is the process of removing a layer or layers of material, such as oxides or metals, from a silicon wafer.*

Doping *is the process in which selected impurities are impregnated on specific areas of a silicon wafer to change its electrical characteristics.*

The Soviet Microelectronics Industry: Hitting a Technology Barrie

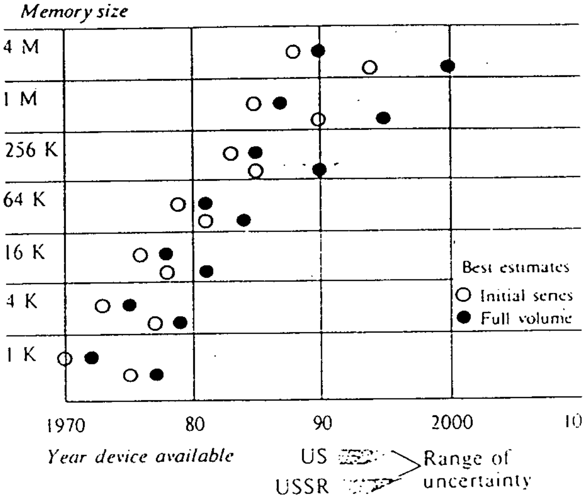
A Struggling Industry

The Soviets, since the early 1960s, have created a large microelectronics research and development (R&D) and production program, imported advanced Western manufacturing equipment, and copied proven Western technology.[1] Despite their efforts, they have been unable to produce complex integrated circuits (ICs) in quantities and qualities commensurate with their large investment in industrial capacity (see inset, "Integrated Circuits"). Today, the USSR's IC production capability is only about one-tenth that of the United States, and Soviet ICs, on average, are about two generations behind the West in technology level

Most Soviet ICs are manufactured at the small-scale (SSI) and medium-scale (MSI) levels of integration. The Soviets are manufacturing growing numbers of large-scale integrated circuits (LSI), but are encountering severe obstacles in manufacturing high-quality advanced devices, such as memory and microprocessor circuits at the very-large-scale integrated (VLSI) level. Although the Soviets achieved full-volume production of the 64K dynamic random access memory (DRAM) (first-generation VLSI) in 1984, device yields are well under 10 percent (compared with device yields of over 85 percent in US plants) and reliability is a problem. [redacted] that the USSR has a dearth of 64K memory chips, while the West is marketing 1-megabit devices (second-generation VLSI) in large volum

Figure 1 compares production milestones for DRAMs for the United States and the USSR. The design structure of DRAMs is simple and repetitive, and DRAM production is constrained mainly by processing technology. Hence, they are a good indicator of the relative technology level of IC manufacturing. As the figure indicates, the Soviets narrowed the US lead in DRAM technology to three to four years in the late 1970s and the early 1980s when they introduced devices at the LSI and first-generation VLSI levels. With the emergence of second-generation VLSI devices, however, that gap has widened to eight to nine years. The Soviets have achieved only pilot to limited-volume production of second-generation VLSI devices; we do not expect them to achieve full-volume production of the 256K DRAM until about 1990 and production of 1-megabit memories until the mid-1990s.

Figure 1
DRAM Production Milestones, US Versus USSR



---

[1] The term "Western" used herein includes the United States, Western Europe, and the industrialized countries of East Asia, notably Japa

Integrated Circuits

Microelectronics—the microminiaturization of electronic components in the form of the integrated circuit—has revolutionized military and commercial electronics and has spurred most of the world's technological achievements of the past two decades.

Integrated circuits are electrical devices that combine many components such as transistors, diodes, capacitors, and resistors into a miniaturized circuit. Many ICs are processed on a thin wafer of semiconductor material, usually silicon. They are subsequently tested, separated, and packaged individually.

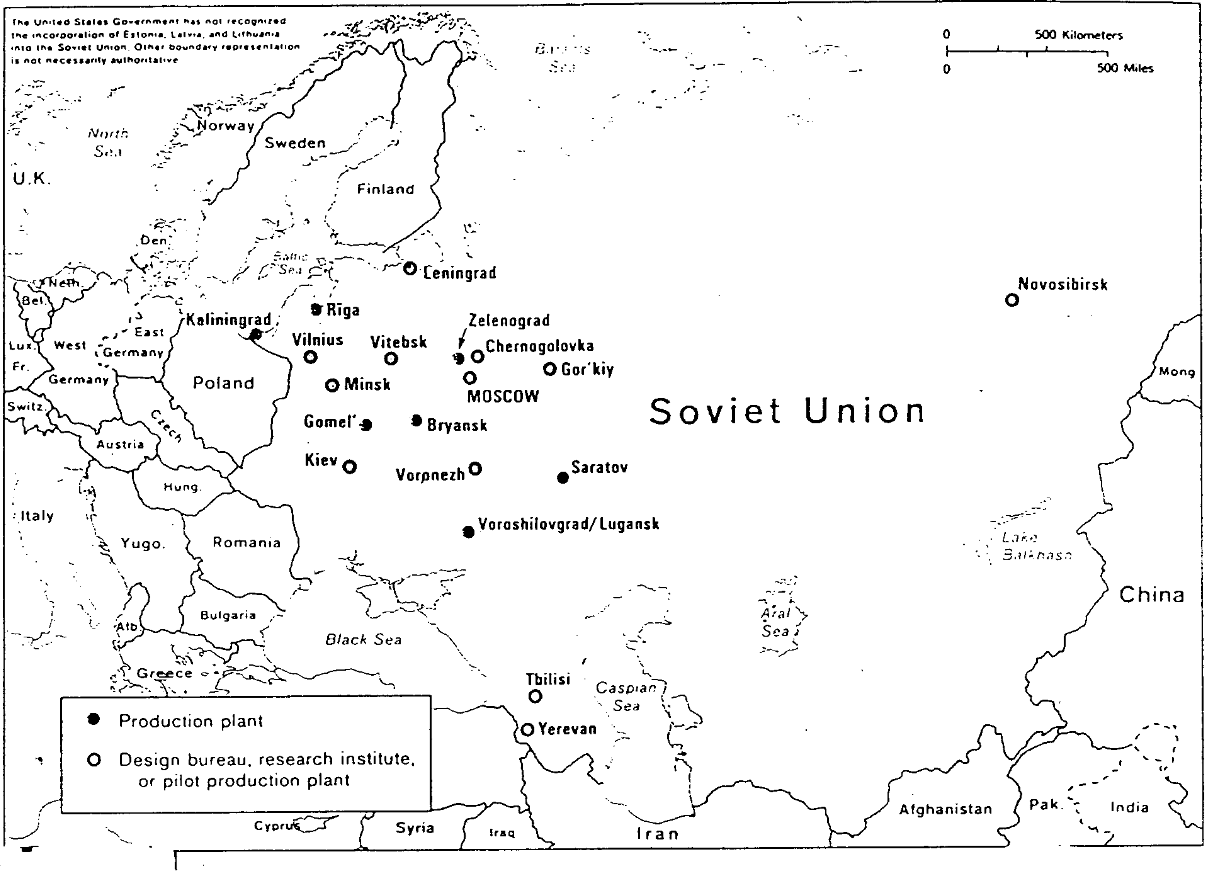
The semiconductor industry is perhaps the only industry that reports its progess on a logarithmic scale. In 1958 an IC contained a single circuit; today's ICs contain as many as 1 million memory bits. Integrated circuits can be defined by their relative level of integration, that is, the number of circuit functions incorporated in the device. Increasing circuit density at a microscopic level results in increased reliability and performance of the host system, while decreasing system size and power requirements and decreasing electronics function costs. The level of integration is usually defined by both the number of transistors per IC and the minimum feature size—defined in microns—of circuit elements. (A micron is 1-millionth of a meter.) The levels of IC complexity (Western lexicon) are keyed to representative device types in the following tabulation:

Category	*Transistors Per IC*	*Minimum Feature Size* (microns)	*Representative Device Types*
Small-scale integration (SSI)	*Less than 1,000*	*>10*	*256-bit memory*
Medium-scale integration (MSI)	*1,000-9,999*	*9*	*1K memory* [a]
Large-scale integration (LSI)	*10,000- 99,999*	*5-7*	*4K and 16K memories; 8-bit microprocessor*
First-generation very-large-scale integration (VLSI)	*100,000-300,000*	*3.0-3.5*	*64K memory; 16-bit microprocessor*
Second-generation VLSI	*300,000-3 million*	*1-3*	*256K and 1-megabit memories; 32-bit microprocessor*

[a] *When used with memory chip information, K denotes an ability to store 1,024 bits of encoded data.*

Even though the Soviets may soon initiate what for them may be defined as "full-volume production" of second-generation VLSI devices, we estimate that production yields for these devices will certainly be well under 10 percent. We judge that one of the major reasons for the Soviets' low IC yield rates and increasing technology lag is the lack of high-quality manufacturing equipment. Second-generation VLSI chips present the Soviets with formidable manufacturing challenges. With minimum feature size approaching 1 micron and with up to 3 million transistors integrated into a single chip, requirements for sophisticated design, processing, and test equipment are heightened substantially. The Soviets appear to have reached a technology barrier at this level that they may overcome only by producing or acquiring more advanced manufacturing equipment to retool many of their IC production plants. Failure to keep pace with Western VLSI technology would limit severely the Soviets' ability to meet the challenges posed by both advanced US weapon systems and Gorbachev's industrial modernization plans. (See appendix A for a discussion of the growing Soviet demand for advanced ICs

Figure 2
Soviet Microelectronics Equipment Production and Design Facilities



Microelectronics Manufacturing Equipment: The Industrial Base

Microelectronics manufacturing equipment is produced by a sector of the Soviet microelectronics industry. We have identified 42 Soviet facilities that are involved in R&D and production of microelectronics manufacturing equipment and in reverse-engineering and adapting foreign equipment (see figure 2). The bulk of these facilities—about 80 percent—are subordinate to the Ministry of the Electronics Industry (MEP), the defense industrial ministry responsible for R&D and production of electronic components and subassemblies.

Three directorates within the MEP are known to be involved in the design and production of microelectronics manufacturing equipment. Many of the equipment manufacturing facilities are subordinate to the

[2] The other 20 percent are subordinate to the Ministries of the Radio Industry, Instrument Making, Automation, and Control Systems Industry, Defense Industry, Nonferrous Metallurgy, and Higher and Secondary Specialized Education Industry as well as the Soviet and Lithuanian Academies of Sciences

Second Chief Directorate (CD), the organization primarily responsible for developing and producing semiconductor devices, including ICs. The Soviets have developed key microelectronics centers in Leningrad, Moscow, Voronezh, and Zelenograd that are organized under the Second CD (see inset, "The Zelenograd Scientific Center for Microelectronics"). Although the primary function of these centers is to produce semiconductor devices, many also produce microelectronics manufacturing equipment. In addition a number of facilities subordinate to the Fourth and the Sixth CDs are also involved in the design and production of microelectronics manufacturing equipment

The Zelenograd Scientific Center for Microelectronics

The Zelenograd Scientific Center for Microelectronics is the closest Soviet facsimile to the United States' Silicon Valley. The Center is composed of several facilities that are engaged in R&D and production of ICs, semiconductor materials, and microelectronics production equipment. Zelenograd is also a focal point for reverse-engineering Western equipment. Although none of Zelenograd's facilities are engaged exclusively in the design and production of microelectronics manufacturing equipment, two in particular—the Scientific Research Institute for the Development of Precision Machine Building (NIITM) and the Scientific Research Institute of Precision Technology (NIITT)—have devoted substantial resources to further developing the USSR's line of wafer-processing equipment

Soviet facilities design and produce equipment that is used throughout the IC production process—from crystal growth through automated testing of individual devices. Appendix B identifies all major Soviet microelectronics equipment design bureaus and production plants and correlates specific equipment lines with each. [redacted]

Analysis indicates that the key facilities for designing, copying, and reverse-engineering microelectronics manufacturing equipment include:

- Electro-Technical Institute *imeni* Ulyanov, Leningrad.
- Design Bureau for Precision Electronic Machine Building (KBTEM), Minsk (see inset).
- Vilnius Design Bureau.
- Research Design Bureau for Semiconductor Manufacturing Equipment, Voronezh.
- Scientific Research Institute for the Development of Microelectronics Equipment, Zelenograd.
- Scientific Research Institute of Precision Machine Building, Zelenograd.

[redacted] a typical equipment design project takes an average of 18 months—including production of the prototype—and that the design of a complete IC production line takes about five years. [redacted] copying a piece of foreign-made equipment can take as little as eight months. MEP often purchases Western IC manufacturing equipment and tasks its design bureaus to copy the design

Many of the Soviets' equipment research institutes and design bureaus have direct links to facilities that are involved in the series production of their microelectronics equipment designs. Analysis indicates that a handful of plants are the leaders in producing microelectronics manufacturing equipment. These are:

- Elektronmash Experimental Production Plant for Semiconductor Machine Building, Minsk.
- Semiconductor Machine Building Plant, Moscow.
- Machine Building and Tool Plant, Riga (see inset).
- Microelectronics Plant Number 111, Voronezh.

Although we lack comprehensive reporting about the level of modernization and performance of all the plants producing microelectronics manufacturing equipment, reporting on individual plants provides a picture of a sector ill-equipped to support a world-class microelectronics industry. [redacted] many Soviet equipment plants are plagued by a lack of quality resources and skilled labor, poor maintenance of manufacturing equipment, and a low level of process automation compared with Western facilities, resulting in poor quality products

The Technology Level of Equipment Used in Soviet Plants

Soviet microelectronics plants are outfitted with both domestic and Western manufacturing equipment. We assess that Soviet equipment—which outfits approximately two-thirds of IC manufacturing lines—is used to produce primarily standard civilian devices. Western equipment, on the other hand, is usually used to produce Soviet state-of-the-art, military-specification ICs

[redacted] analysis of ICs used in standard civilian products confirms the [redacted] assessments of the poor quality of indigenously produced equipment. The characteristics of these ICs indicate that the bulk of the microelectronics manufacturing equipment produced in the USSR generally is well below Western standards in terms of technology and performance and lags Western-produced equipment by one to two generations. To upgrade their average level of IC production from MSI to LSI and early VLSI technology, the Soviets, as did the West, will have to replace virtually all of their current equipment inventory.

Design Bureau for Precision Electronic Machine Building

The Design Bureau for Precision Electronic Machine Building is a major Soviet designer of IC manufacturing equipment. This facility was founded in Minsk in the early 1960s and is organized under the jurisdiction of the Planar Scientific and Production Amalgamation and the MEP. Aside from a small department that reverse-engineers ICs obtained from the West, we have no evidence that KBTEM is engaged in anything other than the design of microelectronics manufacturing equipment. KBTEM is colocated with the pilot production plant Elektronmash, which produces mockups, prototypes, and experimental-test lots and performs limited series manufacture of products designed by KBTEM. [redacted] *described the equipment manufacturing areas as neat, clean, and efficiently layed out with a full range of metalworking equipment* [redacted] *Almost all construction efforts were complete by 1979, and the facilities were operational* [redacted]

KBTEM is also associated with three Planar production plants in Vitebsk, Riga, and Gor'kiy that are involved in the series production of its microelectronics equipment designs. The design bureau is also associated with and designs equipment for other production plants and research institutes throughout the USSR, including the Scientific Research Institute for Micro-Instruments in Riga, the Scientific Research Institute for Micro-Equipment in Yerevan, an institute in Kiev, the Mikron and Angstrem Plants in Zelenograd, and a semiconductor plant in Voronezh. [redacted]

KBTEM and the Planar Amalgamation specialize in the design and production of photolithographic equipment, especially equipment for the production of photomasks (pattern generators, step-and-repeat cameras, and mask aligners); wafer scribes; automatic bonding equipment; automatic probes for IC testing; and IC packaging equipment. With few exceptions, equipment produced by the Planar complex is rarely exported outside the USSR because the domestic microelectronics industry consumes almost all of its output. [redacted] *Planar's microelectronics manufacturing equipment appeared to be competitive with state-of-the-art Western models with respect to raw manufacturing capability and level of automation.* [redacted] *Planar's equipment was not competitive with Western equipment with respect to processing capability for complex IC designs and did not support rapid conversion from one product design to another.*

[redacted]

Soviet state-of-the-art, military-specification ICs usually are produced on more sophisticated manufacturing equipment, much of which has been acquired illegally from the West. [redacted] analysis consistently shows that these devices are of much higher quality than standard chips processed primarily on indigenous equipment—although their performance is substantially below that of Western ICs. We judge that, although much of the equipment used for Soviet state-of-the-art IC production is generally adequate for production of first-generation VLSI devices, production at the second-generation VLSI level will necessitate retooling in the 1990s.

This judgment is based on a comprehensive assessment of the IC manufacturing equipment that the Soviets employ in their microelectronics plants (see

---

Riga Machine Building and Tool Plant

The Riga Machine Building and Tool Plant is the major Soviet producer of IC test equipment.[a] *This plant was founded in 1966 and has been subordinate to the Planar Scientific and Production Amalgamation of the MEP since the early 1970s. Its 5,000 employees produce equipment that is designed by the plant's Special Design Bureau and KBTEM in Minsk, which is also a member of the Planar Amalgamation* [redacted]

Riga stands out as an exception to ordinary Soviet equipment production practices. Most precision instruments plants perform all equipment manufacturing functions from machining through final assembly. The Riga Plant, on the other hand, has three branch plants—in Furmanovo, Vyborg, and Novorzhev—which [redacted] *subcontract for Riga by performing primarily machining functions. There is no finished production at any of the branches: all equipment assembly is performed at Riga.*

[redacted]

Although Riga obtains most of its production machinery and a significant amount of equipment components from Japan, West Germany, France, and the United States, the plant still lacks adequate quantities of quality capital equipment. The plant also experiences problems with poor production techniques, lack of consistent quality control, and bottlenecks in the supply of components and spare parts.

Since 1970, Riga has manufactured exclusively IC manufacturing (and especially IC test) equipment, some of which is copied or reverse-engineered from foreign models. Plant products include laser interferometers, Zond-series automatic test probes, and Okean-, Planar-, and Orion-series microwelders. [redacted] *plant equipment brochures frequently exaggerate key technical parameters by as much as an order of magnitude and* [redacted] *the technological level of Riga's test equipment is about four to five years behind US state of the art*

[redacted] *the equipment products are distributed to about 200 electronics manufacturing plants throughout the Soviet Union, including the Riga Semiconductor Plant, the Angstrem Plant in Zelenograd, and the Svetlana Production Association in Leningrad. Riga also has customers in Bulgaria, East Germany, and Yugoslavia* [redacted] *some of Riga's microelectronics equipment requires more stringent environmental controls, such as temperature and cleanliness requirements, than most of the customer plants can maintain—preventing them from operating the equipment at maximum efficiency or for the duration of the equipment warranties. It is common practice for customers to order extra units so they can cannibalize them for spare parts*

---

[a] *This plant—as well as two Planar plants in Vitebsk and Gor'kiy—are officially and commonly referred to as "Machine Building* Plants*" to conceal their relationship to the electronics indust.*

[redacted]

figure 3 for a description of the production process flow for ICs and appendix C for a detailed outline of IC manufacturing processes and associated production equipment). We have examined each category of equipment—from crystal growth through IC testers—to assess its level of sophistication and its ability to meet the requirements for production of advanced ICs.

Equipment for silicon production and crystal growth includes:

- Furnaces used to convert silicon dioxide (quartz) to metallurgical-grade silicon.
- Distillation equipment that isolates pure silicon compounds—usually trichlorosilane—from the metallurgical-grade silicon.
- Reaction vessels that convert trichlorosilane to intermediate-stage polycrystalline silicon.
- Crystal pullers that produce monocrystalline silicon ingots.

The Ministry of Nonferrous Metallurgy controls the production of electronics-grade polycrystalline and monocrystalline silicon and related equipment. The Ministry's State Scientific Research and Design Institute of the Rare Metals Industry is the primary Soviet organization for semiconductor crystal R&D and oversees the design and production of equipment for th[illegible]ification and preparation of semiconductor materials.

The Soviets produce polysilicon with outdated, small-scale, batch-processing equipment—much of it purchased from the [redacted] before 1980, when COCOM embargoed silicon production equipment and know-how.[4] Although Western producers in recent years have upgraded their production hardware and improved chemical purification processes to improve silicon output, there is no evidence that Soviet producers have done likewise.

In addition to polysilicon production problems, the Soviets have a shortage of crystal pullers for volume production of high-purity, large-diameter (over 4-inch) silicon ingots (see figure 4). Many Soviet sources have reported that domestically produced crystal pullers are of poor quality, and COCOM controls presently restrict the USSR's legal access to Western processes and machinery. Soviet problems in controlling the physical and chemical variables of the ingot growth process have led to low yield rates and low reliability levels of ICs.

Improvements in crystal growth technology, however, may be on the horizon. In the spring of 1988 at a Soviet trade exposition in India, the Soviets displayed an indigenously produced crystal puller with an automated digital-control capability to regulate crystal cross section and to enhance the purity of the ingot. The lack of such an automated control capability reportedly has impeded Soviet IC production.

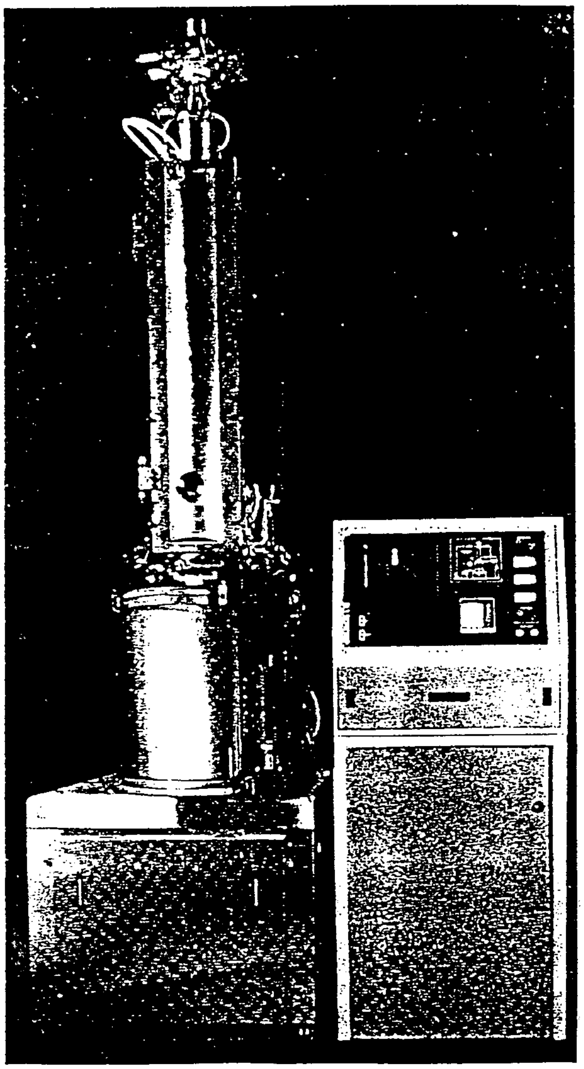


Figure 4. Western crystal puller

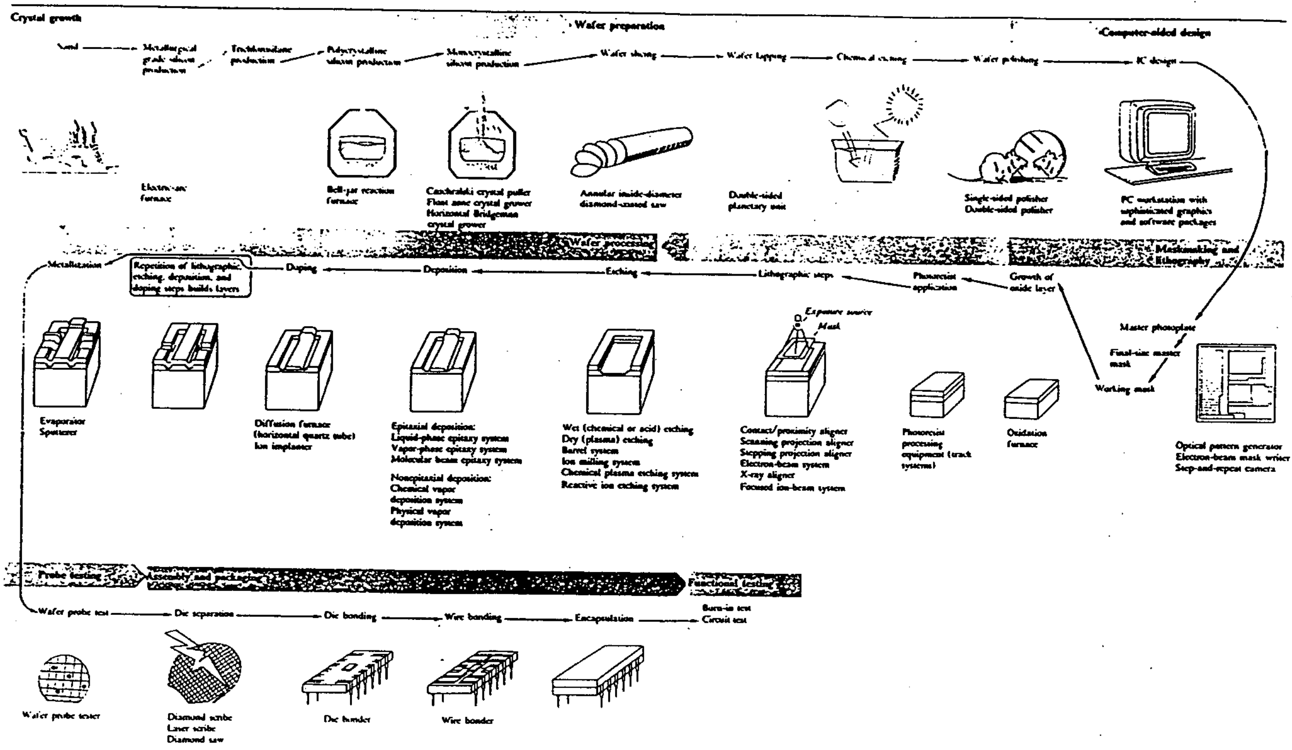
Wafer preparation equipment includes:
- Saws that slice wafers from monocrystalline silicon ingots.
- Lapping machines that smooth wafer surfaces and provide a uniform finish.
- Polishers that produce a flat, mirrorlike surface on the wafers.[5]

---

[4] COCOM, the Coordinating Committee responsible for administering multilateral export controls, was established in 1949 to serve as the forum for Western efforts to control the export of military-related technology to the Soviet Bloc and China. COCOM currently is composed of the United States, the United Kingdom, Turkey, Portugal, Norway, the Netherlands, Luxembourg, Japan, Italy, Greece, France, the Federal Republic of Germany, Denmark, Canada, Spain, Belgium, and Australia.

[5] In the USSR, the Central Scientific Institute for the Organization of the Technology of the Production of Control Systems in Gor'kiy, the Scientific Production Association Svetlana in Leningrad, the Leningrad Optical Mechanical Plant, and the Georgian Polytechnic Institute in Tbilisi have taken the lead in producing and/or reverse-engineering wafer-polishing equipment.

Figure 3
Microelectronics Production Process Flow



The USSR is particularly dependent on Western wafer-slicing equipment because of the poor quality of its own machines (see figure 5). Soviet slicing machines often damage wafers during processing and encounter problems with vibration that demand frequent blade adjustments. Early attempts to reverse engineer US machines reportedly were unsuccessful because the Soviets had difficulty manufacturing and aligning the diamond-coated saws. The Soviets apparently have decided to continue purchasing the saws from the United States or West Germany at a cost of about $100,000 per machine rather than rely exclusively on their own poor-quality ones, which [redacted] are more costly to operate in the long run.

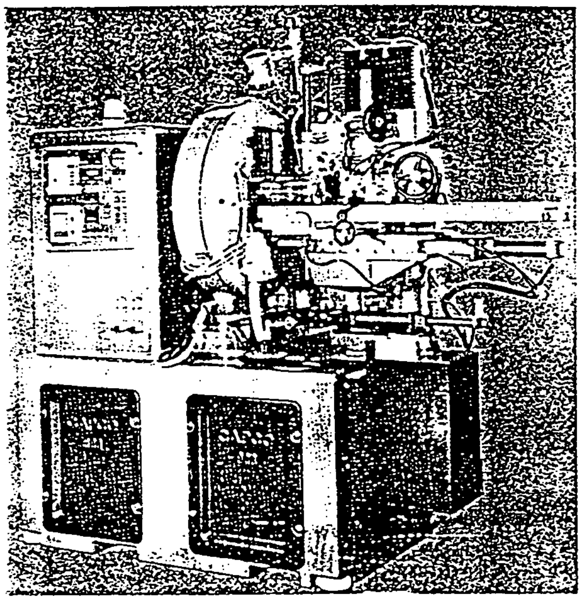


Figure 5. Western wafer-slicing machin

Computer-aided design equipment is used to draw the specific electrical circuit and to prepare that pattern for transfer onto a silicon wafer. As ICs, and especially microprocessors, become more complex, design time becomes exceedingly long. In the West, computer-aided design (CAD) systems have become essential to the IC development process, ensuring high-quality chips while reducing development times

[redacted] The Soviets produced LSI devices using indigenous CAD techniques as early as the period 1972-73. Our technical analysis of Soviet ICs of 1970s vintage is consistent with this information. CAD programs were used to model and simulate the effect of IC design and architectural changes, allowing Soviet designers to modify Western LSI designs to meet domestic requirements

Our [redacted] analysis of 1980s-vintage ICs indicates, however, that the Soviets' CAD capabilities have not kept pace with design requirements—their recent CAD programs evidently are not sophisticated enough to model and simulate the effect of IC changes at the VLSI level of complexity

The Soviets have adopted the practice of copying [redacted] advanced Western devices, in lieu of developing their own designs, to avoid increased IC development times and to aid the development of both new ICs, such as 32-bit microprocessors, and advanced or improved versions of current ICs. [redacted]

Evidence of a Soviet lag in CAD capability in the microelectronics industry is consistent with evidence that the Soviets are constrained by poor CAD systems in other industries, such as aircraft. The Soviets will be unable to meet projected needs at the second-generation VLSI level until they develop or acquire more sophisticated CAD hardware and software to improve integrated circuit design.

Maskmaking and lithography equipment includes:
- Optical pattern generators or electron-beam (E-beam) mask writers that create a photomask of a designed IC circuit pattern.
- Step-and-repeat cameras that optically reduce and reproduce final-size master masks.

[redacted]

- A variety of increasingly sophisticated lithography machines that translate the circuit design onto the silicon wafers.

[redacted] analysis of ICs indicates that shortcomings of maskmaking and lithography equipment limit the performance of standard ICs produced with Soviet equipment but currently are not a limiting factor in manufacturing Soviet state-of-the-art ICs at the LSI level using illicitly acquired Western equipment. These state-of-the-art ICs exhibit very good feature resolution (a measure of circuit density) and alignment accuracy, [redacted] line widths as small as 2.8 microns and alignment accuracies on the order of 0.2 micron. For the next few years, the Soviets may be satisfied with expanded use of scanning projection aligners that offer high throughput and resolutions acceptable for production up to the 256K-DRAM level. Production of more advanced devices, such as 1-and 4-megabit DRAMs, however, will require the Soviets to retool their IC plants with the more sophisticated stepping projection aligners that can handle circuit details at the submicron level and to acquire E-beam lithography systems to produce design masks (see figure 7)

Wafer-processing equipment includes:
- Etching machines that selectively remove patterned layers of the wafer surface exposed during lithography.
- Deposition equipment that deposits metallic or silicon compound films on the wafer surface.
- Doping systems that introduce precise quantities of impurities, or dopants, into specific portions of the wafer to achieve desired electrical characteristics.

Etching, as well as lithography, is a limiting factor in achieving fine-resolution line widths. Although indigenously produced etching equipment limits the performance of standard Soviet ICs, Western equipment now in use contributes to well-defined circuit lines for Soviet state-of-the-art LSI chips. [redacted] analysis shows that the Soviets can produce chips with well-formed, vertical walls, an indication that they have been successful in applying plasma etching techniques to their advanced devices vice acid (or chemical)

In the USSR, the Moscow Design Bureau of Semiconductor Machine Building and the Moscow Scientific Research Institute Pulsar have taken the lead in designing and producing these equipment line

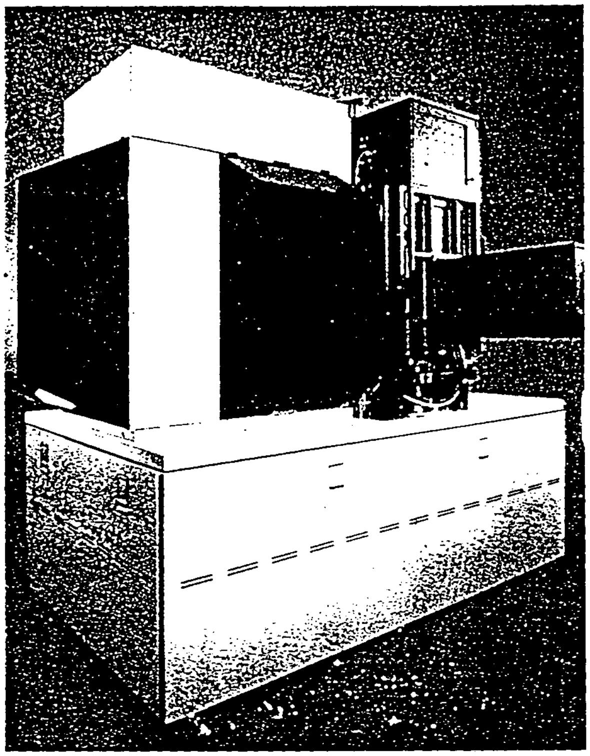


Figure 7 Western electron-beam lithography system

etching—an older process that is used for relatively simple ICs with line widths greater than 3.5 microns. We assess that the use of plasma etching systems will be adequate to meet Soviet processing requirements for first-generation VLSI devices. The Soviets will have to acquire the more advanced reactive ion etching systems to meet upcoming production requirements for second-generation VLSI devices. These systems produce straighter etching profiles and produce ICs at greater throughputs

The Soviets' capability in metallization—the deposition of thin metallic layers on the wafer to interconnect individual circuits on each IC—is perhaps their most serious shortcoming in processing wafers. [redacted] analysis of ICs indicates that the Soviets still use the outdated evaporation technique for processing even their best devices. With evaporation, the Soviets have had difficulty controlling alloy composition on the IC surface, a problem they probably will have to overcome to produce devices at the second-generation VLSI level. The more advanced sputtering technique is usually the method of choice in the West because of its ability to deposit high-quality films at higher rates and at lower pressures and temperatures than evaporation, thereby simplifying production. Although the East Germans market sputtering systems, there is no evidence that the Soviets are yet employing this equipment in their IC production lines (see figure 8).

[redacted] analysis of ICs indicates that the Soviets' capability in passivation—the deposition of an oxide layer on the wafer surface to protectively seal the ICs—also limits the performance of standard ICs processed on indigenous equipment. IC exploitations indicate, however, that illicitly acquired Western passivation equipment is adequate for processing Soviet state-of-the-art ICs. We assess that this equipment will probably support production of second-generation VLSI devices. Current capabilities will probably be adequate until the Soviets begin producing chips at the 4-megabit-DRAM level—a step beyond second-generation VLSI

Electrical components are created on the silicon wafer by introducing selected impurities—called dopants—to areas of the wafer exposed in the pattern etching process [redacted] indicate that the Soviets now use an ion implantation technique in which dopants are ionized, accelerated in a magnetic field, and then physically implanted into the silicon wafer. This technique allows better control of the doping process than the older, conventional diffusion technique, which relied on heat to spread dopants from the wafer surface into the depths of the wafer. Illicitly acquired Western ion implantation equipment probably is adequate to support production of chips up to the 256K-DRAM level. But pilot production of 1-megabit memories will probably force the Soviets to produce or acquire equipment with enhanced computer control.

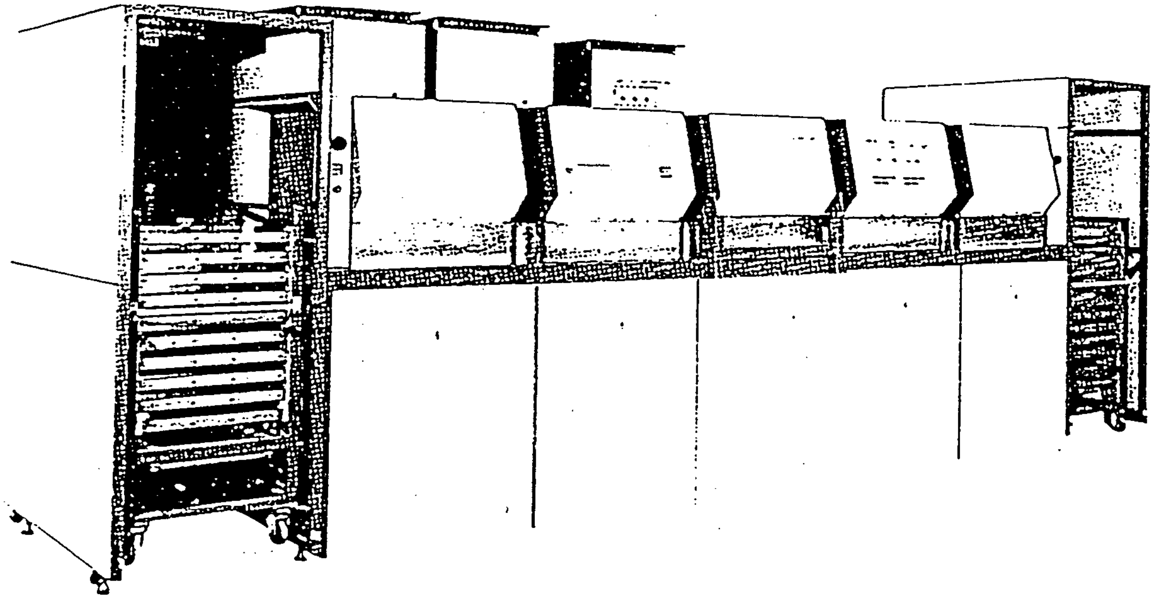


Figure 8. East German high-rate sputtering systen

[redacted]

IC assembly and packaging equipment includes:
- Wafer saws that separate individual ICs on a wafer.
- Die bonders that attach the functional parts of the IC to a package.
- Wire bonders that connect the IC electrically to terminals leading outside the package.
- Machinery that encapsulates the IC in a plastic or ceramic casing

Although the Soviets employ wafer saws that are commonly used in the West, at times they cut only about 30 percent through the wafer, even for their most advanced chips [redacted] The shallow cuts used by the Soviets result in greater fracturing when the ICs are broken free, causing a significant decrease in the number of usable devices. Less advanced Soviet devices have shown cuts of 70 percent or more. Since the only practical advantage of the shallow saw cuts is to prolong blade life, this practice suggests that the Soviets experience spot shortages of quality saw blade:

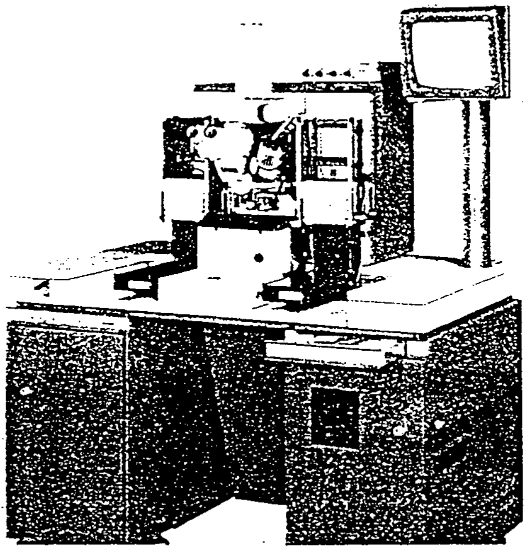


Figure 10. East German automatic wire bond

[redacted]

Through wire bonding, the IC is connected electrically to terminals leading outside the IC package (see figure 10). Our [redacted] analysis indicates that wire bonders currently in use limit the performance of standard Soviet ICs assembled with indigenous equipment [redacted] analysis indicates, however, that illicitly acquired Western wire bonders provide adequate bond strength and shape for most Soviet state-of-the-art devices. Although [redacted] bonding problems in some advanced ICs that at times have contributed to device failure [redacted] we believe that Western equipment now in place may be marginally adequate to meet bonding requirements for second-generation VLSI devices

Testing equipment is used throughout the IC production process to measure critical dimensions and to assess electrical and functional characteristics to identify bad circuits before time and money are invested in bonding and packaging.[8] This is particularly important in the USSR where the failure rate of ICs is high. Some tests themselves have been damaging, however, because of faulty test equipment or procedures [redacted] analysis indicates that improperly adjusted wafer test probes sometimes cause significant damage to Soviet ICs [redacted]

Once packaged, military-use ICs are subjected to rigorous testing to identify parts that would fail soon after first use and to verify that an IC works properly at its intended operating speed. Soviet scientists claim that one of the most acute problems confronting the Soviet microelectronics industry is the lack of equipment adequate to test LSI and VLSI devices (see figure 13). They allege that such equipment can be obtained only from Japan or the United States.

Clean rooms are specially designed areas for wafer-processing operations that have temperature, humidity, and dust control systems. As ICs become more

---

[redacted] indicates that since the 1970s the Riga Machine Building and Tool Plant has taken the lead in the development and production of automated IC testing equipment in the USSR

[redacted]

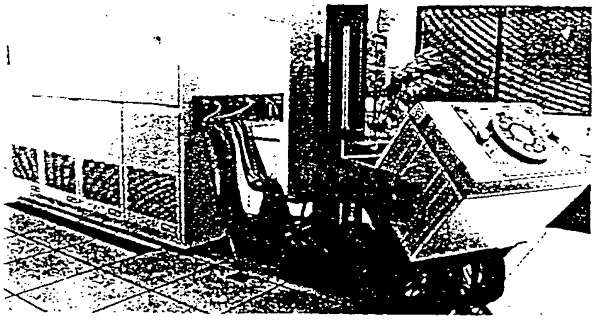
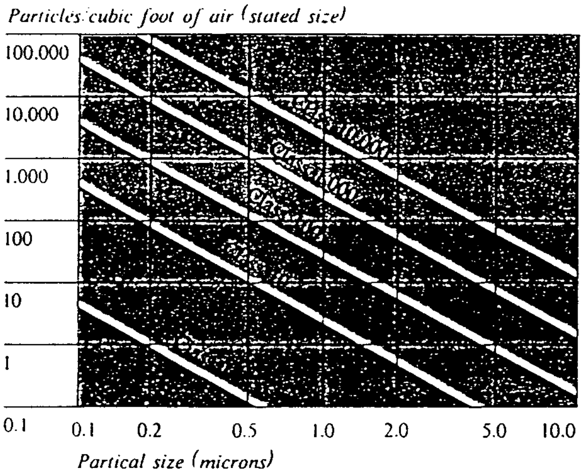


Figure 13. Western VLSI tester

complex and device geometries shrink, stringent clean room environmental control becomes increasingly vital to achieving high product quality and reliability. For example, a single bacterium on a 2-micron circuit line would be equivalent to a large tree across a road. At 1 micron, even a particle the size of a flu virus can disrupt the operation of a chip

Figure 14
Clean Room Classifications



Clean rooms in the microelectronics industry are classified in five standard categories: class 10,000; class 1,000; class 100; class 10; and class 1. The classes refer to the maximum number of particles of a 0.5-micron size or larger per cubic foot of air (see figure 14). Wafer-processing clean rooms must be maintained at least at the class 100 level for VLSI production [redacted] few Soviet IC plants have class 100 facilities; in the USSR, microelectronics plants typically operate clean rooms at the class 1,000 level or above. The lack of adequate clean room facilities has long hindered the USSR's ability to produce ICs at yield rates comparable to those achieved in the West. Over the years, analysis of Soviet devices has shown high levels of device contamination and moisture damage from poor control of the clean room environment

To improve their clean room technology, the Soviets need to develop or acquire high-efficiency particulate air filters and the know-how required to use them in an overall clean room layout. Beyond air filters and clean room design, the Soviets must tighten controls on particulate contamination from incoming gases and processed liquids and from human operators. Humans shed an enormous number of microscopic particulates and have been proved in US studies to be by far the greatest pollutant of IC fabrication areas.

Past Efforts To Reequip the Production Base

The Soviets have tried a combination of measures—domestic R&D and production programs, cooperative efforts within CEMA, and acquisition of Western manufacturing equipment—to reequip their industry to support production of advanced ICs [redacted]

Domestic Equipment Industry

[redacted] has stated that IC production equipment designers and manufacturers are not up to the task of the accelerated development of the Soviet microelectronics industry or the proposed rates of modernization. He notes that the USSR produces only about 10 percent of the volume of IC manufacturing equipment made in the West. [redacted] that the Scientific-Technical Association Factory for the Production of Scientific Instruments in Chernogolovka cannot produce enough advanced deposition equipment to meet all orders, and poor packaging and handling procedures at the Gomel' Radio Technical Plant have resulted in the damage of 70 percent of all CAD equipment shipped to consumer [redacted]

The Soviet equipment production base is insufficient, in part, because IC producers do not retool often, thus limiting the demand for more and better equipment. Reporting indicates that the Soviets expect their equipment to operate for about seven years, and typically it remains in service much longer than this projected lifetime—albeit with extensive downtime and degraded performance. In contrast, US microelectronics producers generally replace 80 percent of their manufacturing equipment every three to five years—each time they initiate production of a new generation of device [redacted]

Sluggish retooling schedules reflect, at least in part, an overriding priority on the part of IC producers to meet state quantitative production plans at the expense of qualitative goals for more reliable and more sophisticated devices. In 1985 the Soviets attempted to correct this situation by introducing a decree that would allow plants to decrease production quotas in compensation for time lost in retooling. There is little evidence that this decree has yet fostered much industrial retooling, but, if implemented, it could counteract industrywide preoccupation with meeting current production schedules and encourage factory managers to favor innovation over maintaining the status qu [redacted]

Bureaucratic problems have also thwarted the productivity and modernization of the microelectronics industry. Production targets assigned the MEP have been overwhelming and unrealistic. Major elements of Gorbachev's industrial modernization program are intrinsically contradictory.[9] Industry is being forced to do everything at once: retool, increase quality, conserve resources, change product mix, and accelerate production. Without a coherent, workable plan, progress has been slo [redacted]

In summary, Gorbachev's modernization program has yet to have a major impact on the Soviet microelectronics industry, which entered 1989 with many of the same problems it had when Gorbachev came to [redacted]

---

[9] The phrase "modernization program" has often been used by Western observers as an umbrella term to describe any policy instituted by Gorbachev for dealing with the USSR's economic problems. As Gorbachev has used it, however, the term has a more limited meaning and refers to his efforts to upgrade the country's stock of plant and equipment. Basically, it involves substantially increasing the productive capacity of the machine-building sec the primary source of manufacturing technology and equipme

power—low worker productivity, poor-quality machinery, and an organizational structure unprepared for economic reform:

- Gorbachev's "human factor" initiatives—discipline, temperance, and improved work incentives—were intended to raise labor productivity for the 12th Five-Year Plan (FYP) while industry retooled. Improved discipline helped boost productivity in 1986, but by June 1987 Gorbachev complained that momentum had been lost.
- Despite rising investment over the course of the current FYP, the Soviets have fallen far short of their plan to bring new capacity on stream and to replace obsolete manufacturing equipment.
- Soviet measures to introduce self-financing and other economic reforms to increase operating autonomy have caused plant officials to flounder. Confused by contradictory directives from above, many have struggled to find reliable suppliers and to meet contract obligations

CEMA Cooperative Efforts

For over a decade, the Soviets have pursued cooperation with the East European member countries of CEMA to augment indigenous microelectronics endeavors and to acquire Western technology.[10] They have set up an elaborate division of labor within CEMA to help create a unified basis of IC technology, microelectronics production equipment, and semiconductor materials. As part of this effort, Moscow has initiated a number of multilateral and bilateral cooperative efforts to coordinate the development, production, and trade of microelectronics production equipment within the Blo

In the early 1980s, the Soviets initiated the Microelectronics Element Base, a multilateral program with the avowed goal of increasing and modernizing CEMA-wide production of microelectronics devices for computer applications. The participants believed, however, that the program's underlying purpose was to match the US Department of Defense's Very-High-Speed Integrated Circuit (VHSIC) Program. Milestones and goals for the Microelectronics Element Base [redacted] have been comparable to those openly published for the US program, namely to produce ICs embodying advanced VLSI technology to meet primarily the high-speed signal processing needs of next-generation defense systems. To support production of these advanced devices, the USSR issued a catalog of microelectronics manufacturing equipment requirements to all CEMA participants, using Western—mostly US—equipment as reference systems.

In 1985 the Soviets initiated another major CEMA cooperation effort, known as the Comprehensive Program for Scientific and Technical Progress to the Year 2000 (CEMA 2000). This program was designed to serve as a blueprint for accelerating the development and diffusion of advanced technologies—including microelectronics—within the Soviet Bloc. An ultimate goal of the program is to reduce Bloc dependence on the West and to increase the region's immunity from Western embargoes and boycotts. The Committee on Cooperation in Electronization is to coordinate the electronics-related agreements and goals that are pertinent to the CEMA 2000 program. By August 1988 this program covered some 35 electronics-related agreements among the member countrie

We know little about CEMA progress in meeting multilateral program goals but doubt that these elaborate efforts have contributed much to the advancement of Soviet state of the art in microelectronics manufacturing equipment. The programs are off to a slow start, and Moscow has complained of a lack of tangible results

---

[10] The East European countries of CEMA include Bulgaria, Czechoslovakia, East Germany, Hungary, Poland, and Romania.

In addition to the many multilateral programs the Soviets have initiated within CEMA, the Soviets in the 1980s have increased bilateral cooperative development and trade accords with its East European CEMA allies. In fact, Moscow has signed bilateral agreements, similar in form and content to the CEMA 2000 program, to cover economic relations with each of its CEMA allies through the beginning of the next century. Many of these bilateral accords have included specialization in the development and production of IC fabrication equipment (see table).

Among the CEMA countries, the USSR can gain most through cooperation with East Germany. The East German combine Carl Zeiss Jena is Eastern Europe's leading producer of microelectronics manufacturing equipment and is renowned within CEMA for its lines of maskmaking and photolithography equipment. It ships much of its equipment output to the USSR (see inset, "Carl Zeiss Jena: A Model Combine"). [redacted]

[redacted] Although Carl Zeiss alleges that its equipment is within two to three years of Western state of the art, we assess that the combine's equipment is still substantially less reliable than Western counterparts and cannot support series production of second-generation VLSI devices. East Germany's inability to meet even its own needs for advanced IC manufacturing equipment is proved out by its heavy reliance on Western equipment.

[redacted] East Germany has emerged as the technological leader in IC technology within the Warsaw Pact. Acquisition of [redacted] equipment was critical to East Germany's success in 1988 in initiating production of second-generation VLSI devices. Although this equipment most likely will remain in East German plants, the Soviets through East Germany may gain access to VLSI manufacturing technology.

Through their relationship with Bulgaria, the Soviets have hastened production of indigenously designed IC manufacturing equipment. The Siberian Branch of the Soviet Academy of Sciences designed the KATUN-V epitaxy system but was unable to kindle MEP interest in manufacturing the machine in the USSR. The Siberian Branch was able to reach a licensing agreement with the Bulgarians, however, and viewed this cooperative effort as the quickest way of introducing this advanced technology to industry. This Soviet-Bulgarian effort has led to the establishment of a joint scientific and engineering center to foster development of other manufacturing technologies.

CEMA cooperation and specialization programs have improved technical capability within the Bloc, reduced duplication of effort in equipment development, increased the level of circuit standardization, and allowed the Soviets to better manage the legal and illegal acquisition of Western production equipment. In addition, by increasing the level of science and technology (S&T) cooperation with Eastern Europe, the USSR has the potential to foster greater political and economic interdependence among the CEMA countries, conserve scarce hard currency supplies, lessen dependence on the West, tap into pockets of technological expertise that exist in Eastern Europe, and concentrate on more advanced technology development programs.[11] In many instances, however, CEMA cooperation has been forced by a heavyhanded USSR that has aroused the resentment of the East European countries.

Acquisition of Equipment From the West

To compensate for their own industry's inability to produce high-quality microelectronics manufacturing equipment in volume, and their inability to satisfy this

[redacted]

Selected Soviet-East European Bilateral Cooperation Agreements in Microelectronics Production Equipment

---

Carl Zeiss Jena: A Model Combine

East German leaders tend to single out the Kombinat VEB Carl Zeiss Jena (CZJ) as the model industrial combine. Looted and completely destroyed by the Red Army immediately after World War II, CZJ reassembled and strengthened its R&D and production programs to become one of the largest and most technologically advanced enterprises in the country. The combine, headquartered in Jena and subordinate to the Ministry of Electrical Engineering and Electronics, now employs over 50,000 employees at 24 subordinate enterprises

The combine is recognized as a world leader in optics technology and its manufacturing range currently extends to over 800 products—from glass, to fiber-optic cable, to cameras for remote sensing. CZJ has become more active in the microelectronics field in recent years, and microelectronics fabrication equipment is one of its newest product lines [redacted] *the US embargo on the sale of such equipment to the Soviet Bloc forced the combine to develop and manufacture its own line of machinery. The combine is now the principal supplier of E-beam lithography systems in the Bloc and produces a wide range of microelectronics equipment, including CAD systems, optical lithography equipment, photomask comparators and inspection equipment, resist coating and developing equipment, ion beam etching systems, chemical vapor deposition equipment, evaporation and sputtering equipment, line measuring systems, wire bonders, and IC testing equipment*

CZJ produces over $2 billion worth of electronics and optics equipment annually. [redacted] *exports approximately [illegible] percent of its microelectronics equipment output to other CEMA countries, chiefly the USSR.* [redacted] *that Zeiss was in the process of equipping several Soviet IC manufacturing plants and emphasized the USSR's dependence on the combine for supply of critical equipment. The USSR's demand for advanced equipment, however, may be met at the expense of East German domestic requirements. For example, Zeiss's lithographic-related products are given priority over optical instrumentation products badly needed by East German labs*

---

shortfall through CEMA cooperative efforts, the Soviets have made a major effort to acquire Western machinery for reverse-engineering purposes and for direct use in their own plants. The USSR usually attempts to reverse-engineer the first sample of Western equipment it acquires. The Soviets have been particularly successful in adapting proven Western designs and incorporating the adaptations into microelectronics production lines [redacted] these Soviet copies seldom, if ever, approach the quality and productivity of the Western originals

Because of time delays and problems in reverse-engineering Western equipment, the USSR often uses large numbers of illegally acquired Western manufacturing equipment to outfit its most advanced IC production lines. This equipment often is not used to its full potential, but it nevertheless is more productive than Soviet-produced equipment. Analysis indicates that since the early 1970s, the Soviets have acquired over 3,000 pieces of Western microelectronics production equipment, covering the entire spectrum of manufacturing operations. They have acquired most of this equipment through West European diverters, but

[redacted]

their use of Asia as a diversion route is growing.

[redacted]

The Soviets' acquisition effort peaked in the 1970s, a time when trade restrictions were looser than they are now and the Soviets had ready access to some of the most advanced microelectronics technology available in the West. Although most acquisitions during this period were legal, licensed purchases, the Soviets

Means and Methods of Equipment Acquisition

The Soviets use a variety of techniques for acquiring Western IC manufacturing equipment. The Soviet Military Industrial Commission (VPK) of the Presidium of the Council of Ministers is responsible for setting acquisition priorities for one-of-a kind Western equipment that is often used for reverse engineering Soviet copies. The VPK processes requirements from the various equipment design bureaus, validates the requirements, assigns a collection priority to each, and designates collection tasks to one or more organizations. These equipment collectors include the Soviet Committee for State Security (KGB), Chief Intelligence Directorate of the Soviet General Staff (GRU), Ministry of Foreign Economic Relations (previously known as the Ministry of Foreign Trade), State Committee for Science and Technology, State Committee for Foreign Economic Relations, Academy of Sciences, and the East European intelligence services. We estimate that the collectors satisfy about one-third of VPK-issued requirements each year.

The Ministry of Foreign Economic Relations manages the Soviet program to acquire, legally and illegally, production equipment in large volume for direct use. The ministry administers and operates hundreds of foreign trade organizations and firms around the world. This global presence and the ministry's official duties make it a practical cover organization for hundreds of KGB and GRU officers involved in technology acquisition.

The Ministry of Foreign Economic Relations keys its acquisition efforts to requirements issued by the various microelectronics manufacturing organizations. Once it approves and prioritizes collection requirements, the ministry arranges for Western contract trade diverters to work with Soviet foreign trade firms to organize large-scale acquisitions of controlled equipment. The Soviets engage over 300 firms in more than 30 countries in their diversion schemes.

The Soviets have dealt primarily with West European trade diverters. [redacted]

Although the Soviets have arranged most equipment diversions through Europe~~, their use of Asia as a diversion route is growing~~. [redacted]

The nonindustrialized countries have served primarily as conduits for the transfer to the Soviet Bloc of microelectronics technology and equipment illegally acquired from industrialized countries. Countries such as Brazil, South Korea, and India potentially can provide the Soviet Bloc with much needed technology and would be attractive acquisition targets because of less stringent export control regulations.

maintained an illicit program to acquire embargoed equipment. Total known acquisitions of major Western microelectronics manufacturing equipment averaged 260 per year between 1972 and 1982, but we believe that the actual number was higher

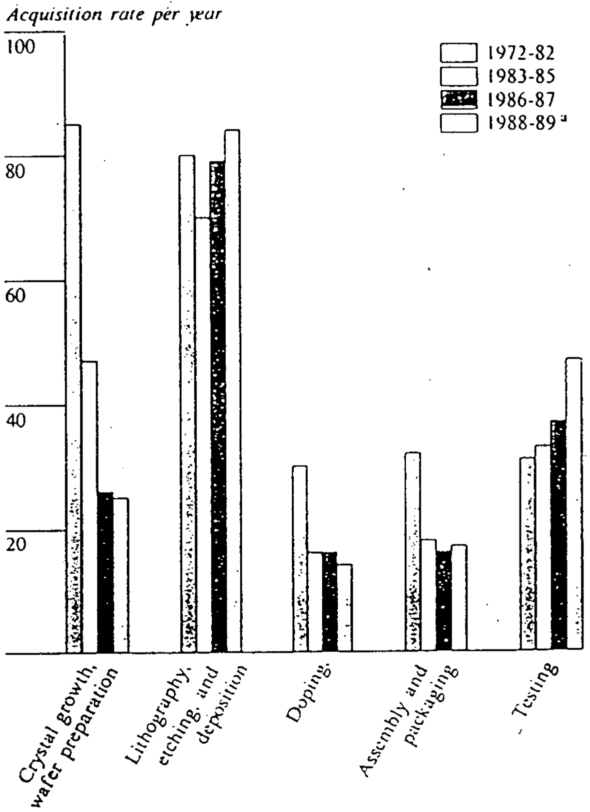
Since the early 1980s tighter trade controls—particularly in the areas of microelectronics and computers—combined with a refinement of the Soviets' acquisition effort for microelectronics manufacturing equipment has resulted in a 30-percent drop in the overall equipment acquisition rate (see figure 15). The average rate of known acquisitions fell from 260 per year to about 180 per year at present,

During this time frame, the Soviets focused their efforts on obtaining fewer yet more advanced and productive machines, concentrated in areas of technological weakness. Analysis indicates that the Soviets have maintained a much lower acquisition rate for some equipment types; the rate has fallen almost 70 percent for material preparation equipment and about 50 percent for doping and packaging equipment. They have maintained a high acquisition rate for oxidation, lithography, and etching equipment and are placing an increasing priority on the acquisition of testers.

These acquisition trends are consistent with our assessment of Soviet progress in overcoming technological deficiencies. Although the Soviets still have some problems with material preparation, doping, and packaging, these problems have lessened in recent years. In contrast [ ] problems persist with advanced lithography, etching, and automatic test equipment—areas where they have maintained high acquisition rates. Soviet efforts to obtain wafer probes and advanced IC testers have been especially rigorous in recent years, and the Soviets have often been willing to pay twice the list price for Western models

Much of the sophisticated equipment acquired by the Soviets for VLSI production, however, requires more stringent environmental controls than most of the Soviet plants can maintain to operate the equipment at maximum efficiency and to achieve acceptable IC

Figure 15
Average Soviet Acquisition Rate of Microelectronics Production Equipment



[a] Collection of information on Soviet microelectronics production equipment acquisitions through technical means abruptly dropped by a factor of 2.5 in 1988 and 1989. Our numbers for 1988 and 1989 reflect an offsetting compensation for this drop in processing capability, and for 1989, an extrapolation for the remainder of the year based on the first five months of reporting.

yield rates. To complement their equipment acquisition program, the Soviets are also seeking advanced clean room facilities from Western firms to outfit their most advanced plants

Without their major equipment acquisition effort, the Soviets almost certainly would lag further behind the West in both IC quality and IC production quantity. We estimate that, without the acquisition of Western equipment for direct use or for use in developing equipment models, the Soviets might not have been able to supply adequately up to 50 percent of their current production lines for SSI and MSI devices. Without this Western equipment and technology, the Soviets' production yields for these devices might have dropped by as much as 50 percent of current values. The impact of Western equipment acquisitions on LSI production is even more significant. Without Western equipment for direct use or for use as models, we believe that the Soviets might have been unable to supply up to 90 percent of their current production lines for these devices and that their production yields might have dropped by as much as 75 percent of yields now achieved.[2]

To supplement illicit equipment acquisition efforts, the Soviets have begun to explore joint ventures with Western firms to obtain microelectronics technology and manufacturing know-how and to facilitate the production and marketing of Soviet-designed manufacturing equipment. The available information indicates, however, that few of these attempts at joint ventures in microelectronics have jelled. Moreover, the agreements that have been concluded are still in the early stages and have yet to make a major contribution to meeting production needs:

- In 1986, in an initial effort to cooperate actively and legally with Western firms in the electronics field, the USSR formed the Science Technology Corporation (STC) to design, manufacture, and market high-technology instruments. This Leningrad-based organization reportedly is governed under relaxed bureaucratic rules governing foreign trade and hard currency. STC has developed a molecular-beam epitaxy system that it claims is available for export, and has concluded a partnership agreement with the UK firm Vacuum Generators, Ltd. to develop by 1990 advanced metallization and lithography systems. STC reportedly is interested in forming joint-development and marketing ventures for advanced instruments with US firms.
- In 1987 the Soviets formed the joint-venture company Interquadro with French and Italian firms [redacted] [redacted] Interquadro will use Soviet software and French hardware to develop and market turnkey workstations for applications such as CAD and electronics testing and debugging, to provide user training, and to service its own equipment [redacted] contributed 70 percent of the initial capitalization, and profits are to be shared proportionately with the Western partners.
- A 1989 *Izvestiya* article disclosed that the Soviets are negotiating a joint venture for the production of an indigenously designed epitaxy system with firms in the United Kingdom, Luxemburg, France, and Sweden. The article described the KATUN-V molecular-beam epitaxy machine as a high-quality IC processing device "equal to prevailing world standards."

Plant Modernization Requirements for the 1990s

The Soviets' relatively antiquated IC production base will be stressed even further by growing demands for advanced ICs from both the military and civilian sectors (see appendix A). To produce high-quality, advanced devices to meet future requirements, the Soviets will have to increase IC yield rates and improve manufacturing practices for VLSI devices. This means they must retool a large percentage of their IC production lines with advanced equipment.

The lack of information on equipment inventory and utilization of microelectronics plants precludes quantification of the Soviets' equipment shortfall in microelectronics production equipment and makes it difficult to estimate requirements for equipment to

---

[2] The derivation of these numbers is explained in DI Intelligence Assessment SW 86-10062 December 1986, *Microelectronics: Impact of Western Technology Acquisitions*,

support future modernization efforts. In an effort to gauge potential investment requirements for needed equipment, however, we looked at past Soviet efforts to acquire Western manufacturing equipment, much of which was put to use in advanced Soviet IC production lines. Analysis indicates that the 3,000 plus pieces of equipment the Soviets are known to have acquired from the West since the early 1970s would be sufficient to outfit approximately 24 IC production lines like those used in the West. We believe that the Soviets have illicitly acquired a significant amount of Western equipment [redacted] and judge that the total amount of Western equipment acquired by the Soviets could outfit as many as, but probably not more than, 75 IC production lines—approximately one-third of their production capacity [redacted]

We think it is reasonable to assume that requirements for VLSI production will require a similar reequipping effort. Analysis [redacted] indicates that the Soviets have at least 70, and possibly more than 100, microelectronics production plants. Although we do not know with certainty how many of these plants are involved in the series production of integrated circuits, for the purposes of this paper we assume that the Soviets have 70 IC production plants. If these plants are outfitted in a manner similar to US plants, we estimate that the Soviets have approximately 230 IC production lines. If we assume that the Soviets choose to retool one-third of those lines for VLSI production,[13] we estimate that they could need the following types and numbers of IC processing equipment:

- 1,150 projection lithography systems.
- 385 photoresist processing tracks.
- 620 plasma etching systems.
- 2,670 oxidation and diffusion furnaces.
- 330 ion implanters.
- 1,930 wafer scrubbers.
- 90 epitaxial systems.
- 160 metallization systems

We estimate that this processing equipment alone would cost between $1.1 billion and $1.8 billion if purchased openly on the Western market. This is close to the amount we estimate the Soviets have spent on their microelectronics equipment acquisition effort since the mid-1960s. Acquiring VLSI testers for advanced IC production lines would add substantially to the above estimate as each typically costs over $1 million. In addition to investment for advanced IC lines, the Soviets probably also face substantial investment requirements to improve the production yields and reliability levels of standard, commercial devices, and to raise their average level of IC manufacturing technology to at least the LSI level

Soviet Options for Reequipping the Microelectronics Industry

The options available to the Soviets for retooling their microelectronics industry for advanced VLSI production are the same as those pursued in the past:

- Accelerating indigenous development and production of manufacturing equipment.
- Maintaining research and production efforts within CEMA.
- Increasing acquisition of Western equipment either directly or by transfer through joint ventures with Western companies

Accelerating Domestic Production

The ideal solution from the Soviets' perspective is to revitalize domestic production capabilities. A successful program to design and build IC manufacturing equipment would reduce dependency on foreign technology, increase the Soviet technological knowledge base, and improve the microelectronics industry's ability to respond to Soviet military and industrial requirements

Gorbachev's program to modernize the Soviet machine-building complex—including initiatives to improve quality control and increase decisionmaking authority at the enterprise level—no doubt will have some positive effects on the microelectronics production equipment industry. The quality and technology

---

[13] In an effort to produce the advanced ICs necessary for modern military and industrial systems, the USSR will encounter the same problems faced by East Germany as it pushes its device complexity beyond its production capability. The result of this push in East Germany has been to allow production of a few advanced ICs, but at very low yields. To obtain a large quantity of advanced devices, the Soviets would be forced to devote a disproportionately large percentage of its production lines to advanced IC fabrication—brute forcing the solution

level of Soviet microelectronics equipment will surely improve, especially in the areas of crystal growth, wafer preparation, and IC assembly, but not as quickly as will Western equipment. The Soviets, however, are likely to continue to fall well short in areas such as CAD, lithography, wafer processing, and IC testing

In the final analysis, improving the technology level of the microelectronics industry, like other high-technology industries, depends on the success of Gorbachev's reform program. Gorbachev's program is unlikely, in the near term, to create conditions along the lines of a Western-style market system that will encourage enterprises to respond quickly and routinely to demands for new production machinery. As a result, we believe that Soviet leading-edge production technology probably will continue to lag that of the West by one to two IC generations and that the Soviets, in the 1990s, will continue to rely on outside sources for much of the equipment required for producing advanced ICs

Maintaining Pressure Within CEMA

The Soviets will continue to look to CEMA cooperation to supplement indigenous equipment design and production efforts and their program to acquire Western technology. The recent success of the East Germans in acquiring Japanese turnkey IC production lines, and their resulting success in achieving pilot production of second-generation VLSI devices, illustrates the type of access to East European and Western technology the Soviets hope to acquire through their CEMA relationship

The Soviets, however, probably will encounter growing resistance from East European countries. Most of the East European countries have gone along grudgingly, and selectively, with Soviet-initiated cooperation proposals to placate Moscow and to ensure deliveries of Soviet raw materials. Soviet efforts to increase S&T cooperation in microelectronics will probably be most well received by Bulgaria and Poland—countries that have linked their economies closely to Soviet development and stand to gain the most from increased contact and cooperation. Romania and Czechoslovakia, however, fear losing autonomy and are less enthusiastic about participating. East Germany and Hungary could find new Soviet initiatives a threat to their independence, an encroachment on their proprietary innovations, and a deterrent to trading opportunities with the West

As revealed at the CEMA Executive Committee meeting in May 1988, many East European countries are uncomfortable with the fast pace of Soviet-inspired initiatives to institutionalize planning coordination through CEMA. Even Czechoslovakia, which has been an active supporter of many Soviet-led CEMA integration initiatives, noted the "complexity" of reconciling numerous long-range regional plans with national interests at a time when most CEMA countries are drawing up their own long-range domestic economic plans and are attempting to restructure their economies. In the future, many of the CEMA countries may be increasingly reluctant to surrender control of domestic high-technology programs to the Soviets or to commit resources to projects that would in the end benefit primarily the USSR. To the extent that the Soviet economic reform movement spreads to Eastern Europe, the Soviets could find it increasingly difficult to mobilize CEMA to support Soviet industrial modernization efforts

Continued Dependence on the West

Although the Soviets originally considered microelectronics technology acquisition to be a short-term fix to overcoming their technological lag with the West, the stifling effect this course has had on the development of their domestic industry has hampered their ability to narrow the gap with the West over the long term. For example, our analysis shows that the Soviets progressed to the level of 64K DRAM production fairly easily using a combination of indigenous know-how and Western technology and equipment. At the 256K-DRAM level, however, they experienced increased difficulty in assimilating technology advances, as evidenced by lengthened device development times and delayed production timetables. We believe that the root of this difficulty can be traced to the Soviets' heavy reliance on Western technology. By employing a follower strategy, the Soviets have failed to acquire an extensive knowledge base of the production of either ICs or microelectronics fabrication equipmen

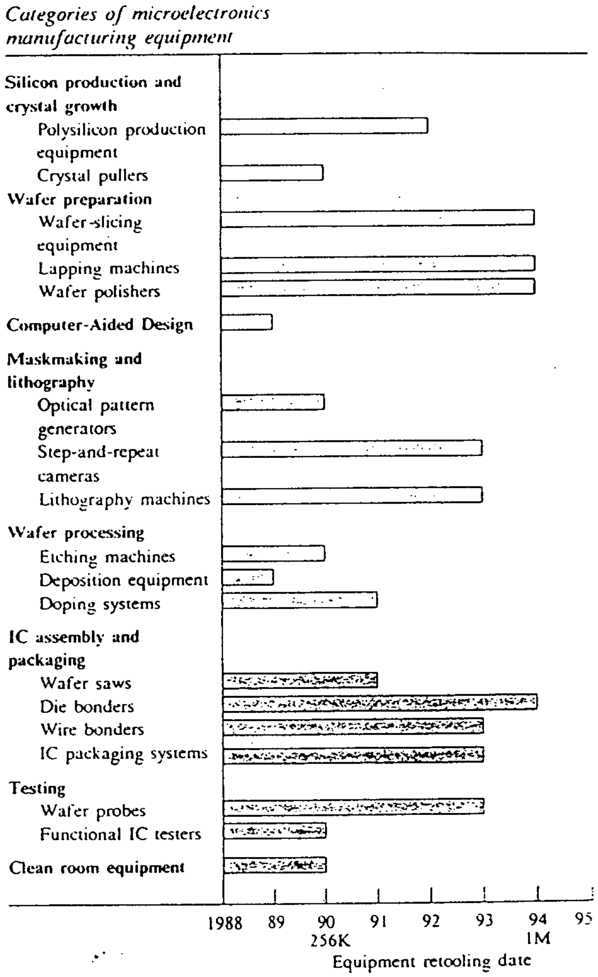
Soviet leaders seem increasingly concerned about the dangers of excessive reliance on Western sources for high technology because of the corresponding depression of domestic initiative and the creation of a built-in lag in domestic technology. These effects are troubling to a leadership that is trying to use a reinvigorated S&T sector as the driving force to improve the economy as a whole. At the 27th Party Congress held in February 1986, Council of Ministers Chairman N. I. Ryzhkov warned Soviet industrial ministers that the party would hold them accountable for their "eager" pursuit of foreign equipment that could be developed domestically. While not ruling out the importation of technology, Ryzhkov called on Soviet industry to rely principally on the "vast scientific potential" of the USSR

Despite public pronouncements about the need to rely on indigenous capabilities, the Soviets will have to continue relying on the West to acquire advanced manufacturing machinery to reequip their microelectronics industry. Figure 16 summarizes the technical capability of the various categories of manufacturing equipment now in use in Soviet microelectronics plants and helps identify likely acquisition targets. The Soviets probably will concentrate on US and Japanese producers to fill their most critical equipment gaps, including CAD, lithography, wafer processing, and IC testing equipment

President Bush announced in May 1989 that the United States will lift its "no exceptions" policy in COCOM. Although the Gorbachev leadership probably views this announcement as an indication that the USSR will have greater access to controlled Western microelectronics equipment, we will not be able to determine the policy's potential impact on Soviet microelectronics capabilities until it has been fully implemented. Meanwhile, the Soviets will continue to exploit any weakness in Western export controls, as well as policy differences among member countries of COCOM, to acquire equipment necessary to produce microelectronics devices required for military and civilian programs for the 1990s and beyond.

In addition, the Soviets probably will push hard to form joint ventures with Western companies for the development and production of microelectronics equipment. We do not yet know the extent to which the Soviets will use joint-venture agreements as a way of acquiring Western production equipment. At a minimum, such arrangements will provide them the opportunity to acquire production knowledge that might otherwise be unavailable to them

Figure 16
Microelectronics Manufacturing Equipment Limiting Factors for Full-Volume Production



Appendix A

Growing Soviet Demand for Advanced ICs

Military Needs

Soviet demand for microelectronics devices has been driven primarily by military requirements. On the basis of our analysis of the number of Soviet military systems probably using ICs, we estimate that production intended for military use is about 400-500 million ICs annually, or about one-third of Soviet production of all types of ICs.

Historically, the military has been the priority consumer of microelectronics devices. The military typically demands and receives the highest quality ICs from Soviet production lines. We do not expect this to change all Soviet military ICs undergo 100-percent reliability testing. Devices that do not pass military inspection standards are downgraded to commercial or export use or are discarded. Chips selected for military application are submitted to electrical, radiation, mechanical, vibration, heat, cold, humidity, and resonance testing well beyond civilian standards.

The Soviet military has long relied on—and invested heavily in—numerical superiority to offset the West's technological advantage. The Soviets, however, are now manufacturing advanced weapons in smaller quantities and are shifting from well-proven to more advanced technologies and from simple to more complex weapon designs to improve weapon performance and to incorporate greater multimission capabilities. Virtually all of these weapon systems rely on microelectronics to provide their expanded capabilitie

We have identified about 30 Soviet military systems that will be likely to require second-generation VLSI devices (that is, 256K and 1-megabit DRAMs) when they are deployed by the year 2000. This represents slightly less than one-third of the systems we expect the Soviets to field at that time. Second-generation VLSI technology, which permits faster data and signal processing, is needed in complex systems that must analyze large amounts of data quickly and accurately. Among its likely weapon systems applications are satellite navigation for submarines, frequency-hopping radars, fire-and-forget missiles, passive sensors, terrain-following radars, and compact electronics for space-limited applications

Development of second-generation VLSI devices will be necessary if the Soviets are to achieve the performance improvements and capabilities needed to counter the next generation of US weapon systems. This does not mean, however, that the Soviets will abandon planned systems if they lack the specified level of microelectronics technology. The Soviets have often deployed systems with degraded performance capabilities because of technology deficiencies in key subsystems. For example, the Soviets have proceeded with production of the Il-86 wide-body civilian transport, even though it has limited range, because the high-bypass turbofan engines required for efficient operation had not been successfully developed by the time the Il-86 reached series production. Moreover, the MiG-29 became operational in 1983 with a less capable lookdown/shootdown radar than originally planned. The key factor governing weapon system development decisions is whether the system contributes to meeting mission goals. If the system fulfills mission requirements, it almost certainly will be produced, even if optimal or intended performance goals are not met

Prime examples of future Soviet weapons systems likely to require second-generation VLSI technology to achieve planned performance include:

- *Stealth bomber.* Second-generation VLSI devices are necessary for sensing systems that rely on passive data acquisition (such as infrared sensors) or on deception (such as a low probability of intercept, frequency-hopping radar), as well as flight control computers for the Stealth aircraft.

- *Stealth air superiority fighter.* A Stealth fighter requires not only passive surveillance sensors but also weapon sensors that will not give away its position. The seeker system for an advanced infrared air-to-air missile will probably require second-generation VLSI devices.

- *AT-6 follow-on helicopter-launched anti-tank-guided missile.* The key performance objective of this system is to achieve a true fire-and-forget capability that would greatly enhance the survivability of the launch platform. An electro-optical seeker on the missile is a means of acquiring such a capability. This seeker would probably require second-generation VLSI devices.

- *Nuclear-powered strike cruiser.* The signal processor of an improved naval surface-to-air missile will probably require second-generation VLSI devices.

- *Carrier with conventional takeoff and landing aircraft.* The carrier's fire control and early warning radars, needed for an improved surface-to-air missile system, will probably require second-generation VLSI devices

Demands for devices required for the development and production of advanced weapon systems, combined with growing consumer demands and ambitious industrial modernization goals will surely stress indigenous VLSI production capability

Civil Needs

Industrial applications account for about two-thirds of annual Soviet IC output, or about 1 billion devices. Most of these ICs are directed to dual military-civilian industrial applications. Soviet use of ICs for what the West would consider true civilian applications—such as educational computers (see inset, "The Soviet Computerization Drive"), home appliances, and automobiles—remains small

Because the USSR's efforts to develop its microelectronics industry have been driven largely by military concerns, historically it has been difficult for Soviet IC producers to ensure adequate deliveries of reliable, advanced devices for commercial and civilian industrial applications. For example [redacted] military priority for acquisition of advanced ICs has limited their

---

The Soviet Computerization Drive

During the 12th Five-Year Plan, Moscow plans to introduce computers throughout the Soviet economy. The plan calls for production of computer equipment to grow by 18 percent annually through 1990—a 130-percent increase over the five years. To support this computerization drive, the Soviets planned to proliferate microelectronics-based technologies substantially during this five-year period

The Soviets, however, have had difficulty supplying enough advanced, high-quality ICs to support this vast program. M.S. Shkabardnya, Minister of Instrument Making, Automation Equipment, and Control Systems, stated at the 1988 Central Committee Machine Building Meeting that the USSR has a specific shortage of 30 million ICs needed to support planned computer production. This shortage of ICs may have had particular impact on the Soviets' ability to meet goals for producing personal computers (PCs

The USSR has an ambitious, publicly stated goal of producing 1.1 million PCs by the end of 1990 to meet demand primarily within its civilian sector. We do not believe that the Soviets will be able to produce even half that amount, in part because of IC shortages. On average, PCs require what amount to Soviet state-of-the-art ICs such as 8086 16-bit microprocessors and 64K DRAMs, and the Soviets appear to have had difficulty supplying their PC programs with an adequate supply of needed devices. For example, they have complained about the low reliability of ICs provided for use in PC production and have reported that they have been unable to meet production goals for some models of school computers because of severe IC shortages

---

availability for use in nuclear power plants. Following accidents at the Sverdlovsk and Zaporozh'ye plants, a special commission reportedly recommended in 1984 that military grade ICs be supplied to nuclear power plants. This recommendation, however, was turned down because of expense and unavailabilty of parts. [redacted] the failure of the computerized control system at the Chernobyl' Nuclear Power Plant in 1986 was caused by poor-quality microelectronic devices, and believes that this accident probably has since forced the Soviets to adopt the use of military-grade ICs in these plants

[redacted] the Soviets have encountered problems in obtaining electronic components to produce new and improved consumer goods. [redacted] the Ministry of the Electronics Industry, which has a virtual monopoly on the production of specialized ICs and other components of automation equipment, falls far short of meeting component requirements for the machine-building complex as a whole. Consequently, the Soviets may be forced to change historical prioritization schemes to meet growing IC demands for consumer goods and advanced production equipment

In the West, advanced ICs, especially microprocessors, are critical components in modern factory automation systems—consisting of computer numerically controlled machine tools, robots, minicomputers, and microcomputers. The Politburo-endorsed 1989 economic plan calls for Soviet industry to increase production of factory automation systems by 80 percent. By 1990, the Soviets plan to incorporate microprocessors or electronic controls in one-third of their machinery—up from 5 percent in 1985

The biggest problem the Soviets face in producing high-accuracy machine tools is their inability to produce microprocessors comparable to those used in Western models. Western importers of Soviet machine tools typically remove the original electronic controls and replace them with high-quality, more reliable Western control devices. We believe that—with certain exceptions—Soviet industrial control systems are approximately five years behind those produced in the West. Most of the Soviets' controllers use 8-bit microprocessors and their most recent units are based on 16-bit microprocessors. By contrast, the 32-bit microprocessor is becoming the building block for the West's computer-automated manufacturing systems. Increasing the integration of the microprocessor control increases the speed and the flexibility of operation. It is clear that Soviet production of LSI or VLSI devices will be critical to the success of Soviet programs to produce and use advanced manufacturing systems

Appendix B-1

Microelectronics Equipment Research Institutes and Design Bureaus

BLANK PAGE

Appendix B-2

Microelectronics Equipment Production Plants

BLANK PAGE

Appendix C

Microelectronics Production: Sand to Circuits

Crystal Growth

The basic material for almost all microelectronics devices is silicon. One of the most abundant materials on earth, silicon is found primarily in the form of silicon dioxide, or quartz. Before it can be used for microelectronics applications it must first be separated from the oxygen and purified of all other contaminants

Metallurgical-grade silicon is produced by smelting quartz-bearing rock in an electric-arc furnace using petroleum coke (carbon) as the reactant. Electric smelting can produce silicon that is up to 99 percent pure. The metallurgical-grade silicon is then dissolved in hydrochloric acid, and the resulting liquid is fractionally distilled to isolate a pure silicon compound—usually trichlorosilane—from a wide variety of other silicon-bearing compounds

Trichlorosilane is the standard feedstock for the production of electronics-grade silicon. In the Siemens process, trichlorosilane is vaporized, mixed with hydrogen gas, and introduced into a bell-jar reaction vessel containing an electrically heated filament. As the reaction progresses, trichlorosilane decomposes and deposits crystals of 99.999 percent pure silicon on all heated surfaces. The reaction continues until a solid rod of silicon has formed around the filament. This rod is composed of millions of randomly oriented crystals known as polycrystalline silicon.

A final step is required to transform the intermediate polycrystalline silicon into finished monocrystalline silicon. The bulk of the world's monocrystalline silicon is produced by the Czochralski method (other methods include horizontal Bridgeman, liquid-encapsulated Czochralski, and float zone) whereby chunks of polysilicon are melted in a crystal puller. This apparatus inserts a "seed" of the desired crystal orientation into the melt and pulls it out slowly, allowing the molten silicon to solidify on the seed. Growth rate and crystal size are controlled by furnace temperature and pull rate. The precise electronic characteristics of each monocrystalline ingot, or boule, are not only determined by the purity and quality of the polycrystalline silicon used in its production, but also by the amount and type of impurities—known as dopants—that are deliberately introduced into the melt.

Wafer Preparation

The monocrystalline silicon ingot is machined to a precise diameter with various flat sides that mark the wafer crystal orientation. The ingot is then sliced into thin wafers, usually by annular inside-diameter diamond-coated saws. The saws may be operated in a semiautomatic or fully automatic mode following the mounting of the boule and its placement for cutting. After slicing, the wafers are cleaned and then lapped to the desired thickness, usually by a double-sided planetary unit that removes equal amounts of material from the top and bottom of the wafer at the same time. Finally, the wafers are chemically etched to remove some of the damage caused by lapping and are polished (using either a single-sided polisher or a double-sided polisher) to produce a smooth, mirror-like surface

Computer-Aided Design

An IC designer uses a computer-aided design (CAD) system to devise the electrical circuit desired and to translate that idealized electrical representation into a multilevel physical IC layout. CAD systems have virtually replaced manual drawing of circuit schematics, whereby individual parts of the IC design were physically drawn many times the size of the actual electrical part, and then photographically reduced for photomask reproduction. The tolerances and geometries used in today's complex ICs make manual drawing virtually impossible. CAD systems are many times faster than hand drawing, are more accurate, and are more reproducible in their results. After the circuit design has been completed, the CAD system furnishes a tape that can be input to either an optical pattern generator, an E-beam maskmaking system, or a direct-writing system to translate the IC design into a working circuit

Maskmaking and Lithography

Following circuit design, pattern generation is the start of optical maskmaking or reticlemaking. An optical pattern generator is generally used to create automatically the photomask of a designed circuit pattern. The output is a master photoplate, usually 10 times (10X) larger than the final circuit. E-beam maskwriters are preferred for the maskwriting process of complex IC designs with fine geometries because the process is accomplished faster than with optical pattern generators.

Following pattern generation, the master photoplate is optically reduced and reproduced hundreds of times in a step-and-repeat process to yield a set of final-size master masks from which the working masks are made. Step-and-repeat cameras are capable of achieving usable line widths of 0.8 micron. Although optical step-and-repeat cameras traditionally have been used to produce 1X master or submaster plates for working prints, directly stepped working masks (drawn by an E-beam process) may now be an economically viable application.

In translating the circuit design onto the wafer, an oxide layer is grown on the wafer surface using an oxidation furnace and that oxide layer is coated with a chemical layer called a "resist," which is sensitive to the radiation source to be used—visible light and ultraviolet light (optical lithography or photolithography), electron beams, X-rays, or ion beams. Photoresist processing equipment—often referred to as track systems—sequentially scrubs, bakes, coats, and develops the wafer and photoresist. One level of the IC design is then patterned onto the resist (device fabrication consists of anywhere from six to 20 photolithographic steps) using a variety of increasingly sophisticated equipment. Lithography represents one of the highest cost elements in producing semiconductor products, and the choice of lithography systems and exposure tools is a delicate balance between cost, performance, and productivity:

- *Contact-proximity aligners* are the oldest and simplest mask-to-wafer pattern exposure machines. Contact exposure is capable of generating minimum feature sizes of only some 3.0 to 5.0 microns and can damage the mask and wafer. Proximity printing lessens the potential for mask and wafer damage, and the best proximity aligners are capable of producing feature sizes as small as 2.5 to 3.0 microns. Top of the line contact or proximity aligners using deep ultraviolet illumination sources are specified to achieve nearly 1.0-micron resolution. Registration problems, however, increase at these line widths, especially with larger wafer diameters. Since the late 1970s, proximity and contact alignment techniques have, in general, been replaced by optical projection lithography in microelectronics fabrication.

- *Scanning projection aligners* use a 1X photomask containing the full wafer pattern and expose it onto a photoresist-coated wafer with a "sweep or scan" of the illumination source through mirror optics. This equipment contributes to long mask life and is capable of achieving a resolution of 0.9 micron. These aligners, however, are relatively expensive, are sensitive to temperature and vibration fluctuations, and require frequent adjustments.

- *Stepping projection aligners (steppers)* project a segment of a full wafer pattern from a 1X reticle—or reduce it from a 10X or 5X reticle—through a lens while "stepping" across the wafer. The choice of available reduction ratios generally is a trade-off between resolution and field size and can be controlled by throughput considerations. This equipment contributes to long mask life and limits defects. It is very expensive, however, and can be subject to distortion and stepping errors. Steppers with excimer laser light sources recently have been introduced that are capable of submicron lithography, and versions now in development will probably be able to fabricate circuit lines as low as 0.25 micron.

- *E-beam systems* have the resolution and alignment accuracy necessary to achieve circuit dimensions down to 0.1 micron. They can be used for maskmaking and direct wafer writing. The primary applications of E-beam direct wafer writing are small-volume production of custom ICs, quick turnaround of new designs, or achievement of submicron geometries. One of the biggest advantages of the E-beam system is its ability to facilitate changes in a pattern to meet design and processing requirements readily. The biggest drawbacks of E-beam systems are equipment expense, low throughput, and proximity effects.[14]

- *X-ray aligners* using synchrotrons as light sources have the potential for high throughput of submicron feature sizes (below 0.5 micron), but researchers have yet to resolve mask fabrication problems. US industry experts predict that X-ray aligners will be necessary for fabricating future 64-megabit memory devices.

- *Focused ion-beam systems*, now in exploratory research, potentially can be used for direct-writing free of proximity effects. Throughput with this system, however, will most likely be low.[15] The use of focused ion beams to repair defects in lithographic masks and ICs and to perform failure analysis, however, has moved rapidly from R&D to manufacturing applications.

After each level of the IC is patterned onto the wafer, either the exposed resist or the unexposed resist is washed away—depending on the type of resist—enabling a wafer-processing step to be carried out on the desired portions of the underlying layer.[16] Following the processing step, the remaining resist is washed away. This process is repeated until the entire circuit has been replicated onto the silicon wafer

Wafer Processing: Etching, Deposition, and Doping

Etching

Etching is a process in which patterned layers of the wafer surface revealed during lithography are selectively removed. Wet (acid or chemical) etching is the older process that is still used for relatively simple ICs with line widths greater than 3.5 microns. Wet etching cannot be used much below this feature size because of its tendency to etch sideways at the same time as it etches downward, causing the lines to spread and merge together.

To overcome this drawback, dry (plasma) etching is used for advanced ICs. Dry etching systems are required for processing ICs with feature sizes of 3 microns and under. There are four types of dry etching systems for thin film etching:

- *Barrel systems* are used for photoresist stripping and selective etching of polysilicon and silicon nitride with circuit geometries of 5 microns or greater.

- *Ion milling systems* have been used to etch gold, platinum, and other materials that are unsuitable for either chemical plasma etching or reactive ion etching.

- *Chemical plasma etching systems* produce an isotropic etching profile similar to wet etching, since plasma chemistry is the dominant etching

---

[14] If two or more pattern geometries are exposed in proximity, each geometry will receive a higher electron dose than if it were remote from all other structures. This mutual exposure effect causes the dimensions of geometries in proximity to be altered from intended values

[15] Compared with standard optical lithographic systems, E-beam, X-ray, and focused ion beam systems offer the potential for producing ICs with smaller feature sizes. Standard optical systems, however, are less expensive, can process more wafers per hour, and suffer fewer operational problems.

[16] With a positive resist the portion of the resist that the light strikes is removed; with a negative resist the areas exposed to light remain after development. Positive resists generally allow for creation of smaller feature sizes

mechanism. These high pressure machines process wafers one at a time and thus have lower throughputs than batch processing machines.

- *Reactive ion etching systems* produce a straight etching profile since the dominant etching mechanism is ion bombardment. These low-pressure machines process wafers in batches.

Each dry etching technique has different characteristics of throughput, spread, and material selectivity. Most systems in production use are highly automated and do not place great reliance on the skill of the operator. Chemical plasma etching and reactive ion etching are by far the most popular dry etching methods, and current systems are capable of etching lines down to about 0.2 micron in width—far beyond what current IC designs require

Deposition

Deposition of films onto the wafer surface can be divided into two categories, epitaxial and nonepitaxial. Epitaxial growth is the more difficult of the two to achieve because it requires the crystal structure of the wafer to be continued through the deposited layer. There are three basic types of epitaxial deposition:

- *Liquid-phase epitaxy* (LPE) is the oldest technique, whereby films are grown by sliding a wafer above the surface of the melted element or compound that is to be deposited.

- *Vapor-phase epitaxy,* which includes metal-organic chemical vapor deposition, uses vaporized chemicals to grow films on wafers. This process has, by and large, overtaken the LPE technique.

- *Molecular beam epitaxy* (MBE) is the most advanced epitaxial technique. MBE deposits films on heated wafers under ultrahigh vacuum conditions. Film growth, while relatively slow (approximately 1 micron per hour), allows very accurate control of film thickness and doping profiles and produces atomically abrupt interfaces. MBE has great utility for depositing exotic compound semiconductor materials

Nonepitaxial chemical vapor deposition (CVD) and physical vapor deposition (PVD) are less demanding processes. CVD can be used to deposit many materials, but those generally deposited (other than epitaxial silicon) are polycrystalline silicon, silicon dioxide, and silicon nitride

PVD is used to deposit thin layers of metals or silicides on the wafer to act as interconnects between individual circuits on each IC. The two methods of PVD are evaporation and sputtering. Evaporation is the conventional method for metal deposition and is often chosen for processes that require low temperatures or high vacuum. The major drawbacks of evaporation are the difficulty in controlling alloy composition and the nonuniform coverage of steps on the wafer surface. Evaporation has, in general, been replaced by sputtering in advanced applications. Sputtering is often the deposition method of choice because of its ability to produce high-quality films at a high rate and at lower temperatures and pressures

Doping

Doping is the controlled introduction of precise quantities of impurities, or dopants, into specific portions of the wafer to achieve desired electrical characteristics. The dopants normally used include boron, arsenic, phosphorus, and antimony

The conventional doping system is a diffusion furnace that relies on heat to spread dopants steadily from the wafer surface into the depths of the wafer. Selective masking with a silicon dioxide layer is used to determine the regions to be diffused. Diffusion of a dopant into semiconductor elements is a function of time and temperature. The greater the desired dopant density, the higher the baking temperature and/or the longer the wafer is heated. The majority of new diffusion furnaces for use in production incorporate computer process control to ensure a high level of accuracy in repetitive diffusion operations

The more recent doping technique is ion implantation, the direct injection of dopant atoms into the wafer. Automated ion implanters are required for processing

ICs with feature sizes of 3 microns or less. Manufacture of complex ICs may involve as many as 10 different ion implantation steps. One of the major advantages of implantation over diffusion is better control of doping profiles because of lower processing temperatures

Assembly and Packaging

Assembly is the step following wafer processing. After the individual ICs on the wafer are sawed apart (using diamond scribes, laser scribes, or small diamond saws), the functional parts (see "Testing" section) are attached to a package in the die-bonding step. Die bonders may be manual, semiautomatic, or fully automatic

Die bonding is followed by wire bonding, the major method used to connect the die electrically to terminals leading outside the package. Wire bonding may be performed manually, semiautomatically, or automatically. Generally, the higher the degree of automation, the higher the quality of the bonds

The final step is encapsulation, or packaging, in which the IC is enclosed in plastic or ceramic. Most commercial ICs are packaged in plastic using a metal lead frame designed for automatic assembly. The most common package type is the dual in-line package (DIP). Plastic DIPs are cheap and easy to manufacture, but are relatively fragile and have poor thermal dissipation characteristics. The more costly, but more durable, ceramic packages are reserved for ICs destined for rigorous environments, such as military electronics systems. High-performance ICs for military and space environments require packages that can protect them from high levels of radiation and vibration and extreme temperatures.

Testing

IC testers include equipment used to test the wafers on line during various processing stages and equipment used to test the packaged device. Optical line-width measurement systems are used on line for the nondestructive measurement of circuit dimensions on photomasks or wafers. Scanning electron microscopes are replacing optical line-width measurement systems for inspecting critical dimensions of 1.5 microns or less

The wafer probe is used for rapid testing of electrical and functional characteristics of die on wafers. A small number of tests are made, although not at the circuit's operating speed. The purpose of the test is to mark defective ICs before time and money are invested in bonding and packaging

Packaged IC testers include both burn-in systems and functional testers. Burn-in systems are used to identify quickly the parts that would fail soon after first use. Batches of ICs are loaded into a temperature- and humidity-controlled chamber, powered up, and allowed to sit for a length of time to simulate long-term normal use. Most weak parts fail at this stage, allowing the IC producer to weed out unreliable devices

Functional testers are used to verify that an IC works properly at its intended operating speed. These testers are usually classified by a combination of two features: the maximum number of pins it can test, and the speed at which it can test the device. These two characteristics are inversely proportional to each other (the more pins a device has, the more time it takes to test it, hence, the need for a faster tester). Sometimes test equipment is also defined by its maximum memory testing capability, for example, MSI, LSI, VLSI, and so forth. The most powerful testers can test devices with 1,024 pins at 200 megahertz. These testers require extensive computing power and software packages that must be updated for each new product development