Chapter 5

Linkages Between HDTV, HRS, and Other Industries

INTRODUCTION

HDTV is possible only through the intensive use of digital electronics; significantly higher quality pictures than today's NTSC cannot be delivered to the home by any other means because of bandwidth constraints. As a result, the core technologies of HDTV-production, storage, transmission, processing, and display of information-are the same as those used in computer and telecommunications devices.

It is often overlooked in the current debate that HDTV is a development vehicle for "High-Resolution Systems" (HRS) generic to all information systems. HDTV proponents, for example, argue that the ability to produce high-performance displays and other technologies gained from a presence in the HDTV market will give manufacturers significant advantages in producing related components and systems for the computer and telecommunications markets. Skeptics resist the linkage argument as an unproven hypothesis and insist that these technologies can be developed by the computer and telecommunications industries independently.

OTA found evidence that HDTV developments *are driving the* state-of-the-art in several of these technologies more rapidly than are developments in computer or telecommunication systems. The enormous amount of information in a real-time, full-color HDTV signal-some 1.2 billion bits per second[1] (1.2 Gbps) in the uncompressed signal-places severe demands on today's technologies. This contrasts sharply with the conventional stereotype of consumer electronics as low-technology products lagging far behind the leading edge of computers and telecommunications.

HDTVS must handle huge information flows and require special hardware to provide high computational speeds to convert a signal compressed for transmission back into a viewable picture. Digital Signal Processors (DSP) tailored to this specific task are meeting that requirement. In contrast, engineering workstations, for example, must flexibly perform a broader range of calculations than an HDTV; therefore, they are software programmable.[2]

The major technological bottleneck for the workstation today is the computational speed and the flexibility of its microprocessor and graphics display chips. Workstations put less stress on communications, storage, and certain aspects of display technologies than HDTV because they do not yet approach the information flows or the (specialized) computational speeds demanded of HDTVS.

Other High-Resolution Systems (HRS), such as desktop publishing and medical imaging, place different and often lower demands on DSP, storage, and communications technologies than does HDTV. They typically do not operate in real-time and accordingly have lower rates of information flow. Many of these other applications also place lower demands on display technologies than does HDTV. They work well enough with slower response times, limited colors, lower brightness, or smaller display areas. Providing sharp images of stationary objects as is usually the case with computer applications is, in many respects, technologically easier than providing high-resolution, real-time, fill-motion video. These other HRSs often require, however, higher resolutions than currently planned for HDTV displays.[3]

While many of the linkages between these technologies are obvious, they are not easily measurable. Nevertheless, these linkages can have an enormous impact on widely scattered technologies and markets. Simple analyses in which the projected future value of an industry is discounted to the present cannot account for the new and unforeseen opportunities that might be created by being in a market. Sony's and Philips' development of the compact disk player, for example, has opened huge markets in computer data storage. Similarly, flat panel

[1] This is for the NHK system. Other systems might have somewhat higher or lower data rates.

[2] Note that "smart" HDTVS would have the capability to be somewhat softwareprogrammable, but are not included here as they are not likely to be sufficiently low in cost for consumer use for some time. Their development will push the state-of-the-art significantly irprogrammable DSP.

[3] Because computer displays are normally viewed closeup and there are eye fatigue issues, some of the design criteria are different.

plasma and electroluminescent displays, among others,[4] drove the initial development of Power Integrated Circuits (Power ICS) which, in turn, are revolutionizing the distribution and control of electric power in equipment ranging from aircraft to air-conditioners.

The linkage argument does have limitations. For example, unlike leading-edge PCs or workstations where performance is everything and price a secondary consideration, HDTVS must be produced and marketed at a price within reach of consumers. This demands exacting design and manufacturing discipline that is often lacking in narrower or more specialized markets, such as the military or medical imaging.

The large potential size of the HDTV market could enable significant improvements in manufacturing technology as firms seek to lower production costs. In some cases, low-cost manufacturing will require pushing the state-of-the-art in component technologies; in others, it will mean that HDTV will let the computer or telecom markets push the state-of-the-art and will then use those results. Above all, HDTV-asfor all consumer electronics—will require pushing the limits of cost-effective manufacturing of sophisticated electronic systems. This might be one of the most important impacts of HDTV.

Whether or not a consumer HDTV market develops, the expectation that there will be a large market is forcing manufacturers who wish to participate to push the state-of-the-art in the various HDTV-related technologies. If the market does develop, then large-volume production might give the producer economies of scale in a number of other components and products.

Having a technology matters little if markets are closed to innovators or the entry barriers are effectively insurmountable. As a result, it is also important for those that develop the technology to capture a significant share of the market. In the past, the United States has assumed that if the technology was developed, markets would follow. Faced with large, usually vertically (and horizontally) integrated, aggressive foreign competitors; and confronted with increasingly skill- and capital-intensive R&D and manufacturing to produce high-technology goods, this assumption is no longer valid.

Neither linkages nor market share nor volume production of computers were sufficient to save the U.S. DRAM business. U.S. firms produce about *70* percent of the world' spersonal computers today and lead the world in PC design. Nevertheless, domestic firms have lost the market for DRAMs to Japanese fins. A combination of factors, including less efficient manufacturing by some U.S. firms on one hand and aggressive foreign trade practices on the other, forced most U.S. manufacturers out of this important market.

The United States has also lost important HRS imaging markets such as low-end copiers, as well as many *other* pieces of the electronics industry, despite having a predominant market share in many of these just a few years ago.

Startups in the U.S. electronics industry are increasingly focusing on design alone and depend on foreign operations for the highly capital-intensive manufacturing operations5—they cannot secure the capital necessary to do the manufacturing themselves. In contrast, a number of foreign firms with little expertise in advanced electronics are becoming important manufacturers of electronics through heavy and long-term investments and careful attention to the manufacturing process. For example, NMB Semiconductor, a new subsidiary of a Japanese ball-bearing company, Minebea, in just 5 years entered and became the world leader in very fast DRAMs.[6] Kubota, a Japanese agricultural equipment company, is now manufacturing mini-supercomputers designed in the United States.[7] Similarly, Korean semiconductor firms are now becoming ‘important producers of commodity DRAMs.

The United States cannot survive by performing R&D alone. Manufacturing provides far more jobs,

---

[4]Others include non-impact printers and multiplexing automobile wiring. In particular, automotive applications are expected to become an increasingly importantdriver of this technology in the next few years. Martin Gold, ‘Autos Drive Smart PowerIC R&D,'' *Electronic Engineering Times,* Jan. 15, 1990, p. 39.

[5]Integrated Circuit Engineering Corp., “Mid-Term 1988,’ Scottsdale, AZ, lists 18 startups during 1984-87 that chose not to build their own fabrication facilities. Of these, at least one-third were using fabrication facilities inJapan, Taiwan, and Korea.

[6]‘‘How NMB Took Over the Fast DRAM Market,'' *Electronics,* November 1988, p. 188; Bob Johnstone, “Chips and Sushi,'' *FarEastern Economic Review,* July 20, 1989, p. 52.

[7]David E. Sanger, “U.S. Parts, Japanese Computer, ” *New York Times,* Sept. 7, 1988, p. D].

greater value-added, and larger cash flows than R&D, and these are needed if future investments are to be made in R&D or production. Nor can we expect every American to earn a living as a design engineer. With the increasingly tight linkages between R&D and manufacturing due to the exacting requirements of modern manufacturing processes and quality control, and due to the need to design for manufacturability, R&D is merging with the manufacturing process. In many cases, when the United States loses manufacturing, the loss of R&D is not far behind.

The problems facing the U.S. electronics industry are much broader than simply HDTV. Although HDTV maybe an important element of any broader U.S. strategy in electronics, by itself HDTV will neither seal the fate nor save the U.S. electronics industry. There are undeniable linkages-some strong, some weak-that should be recognized, but the problems facing the U. S. industry extend into many other financial and structural factors. These include: the higher cost of capital in the United States resulting, in part, in lower capital and R&D investments than our competitors; inattention to manufacturing process and quality, poor design for manufacturability, and separation of R&D from manufacturing; foreign dumping and foreign market protection; and smallness of scale and/or lack of vertical/horizontal integration compared to foreign competitors. Some of these broader issues facing U.S. manufacturing are discussed in a recent OTA report ''Making Things Better. '

SEMICONDUCTORS

The rapid technological advances and cost reductions of digital electronics will likely make HDTV affordable in the not-too-distant future. During the past 10 years, the capacity of leading-edge memory chips (DRAMs) has increased by 250 times while the cost per unit memory has decreased nearly 100 times.[9] Each generation of advanced TVs will use increasingly complex digital semiconductors to provide a better quality picture at a lower cost.

In turn, HDTV will directly push the state-of-the-art in various aspects of digital signal processor (DSP), display, data storage, and possibly semiconductorpackaging technologies, among others. HDTV may indirectly impact a much broader range of components as well as computer and telecommunication systems as a result of these technological advancements.

Digital Signal Processing

There are three steps in digital signal processing. First, the continuously varying analog signals of the real world—sound, light, temperature, etc.—are converted into a digital form usable by computers with an analog to digital (A/D) converter. (See box 4-2.) Second, the signal is processed with a Digital Signal Processor-to decode the tightly compressed broadcast signal back into a recognizable picture, or reduce ghosts and snow (noise) to produce a near-flawless picture. Third, the digital signal is converted back into an analog form-sound and pictures, etc. that people can understand-with a digital to analog (D/A) converter.

A digital signal can be manipulated (as in signal compression), analyzed, transmitted with greater reliability, and stored in computer memory. In general, the more the broadcast signal is compressed to fit into a narrow bandwidth, the more digital signal processing power is required for its reconstruction.[10]

Digital signal processing is used today in compact disk players, facsimile mail, long-distance telephone lines, computer modems, and in other applications. Human hearing and vision are analog, so digital signal processing will play an increasingly important role in providing an 'interface' between people and information systems in the future as we come to rely more on images and sound instead of alphanumeric text.

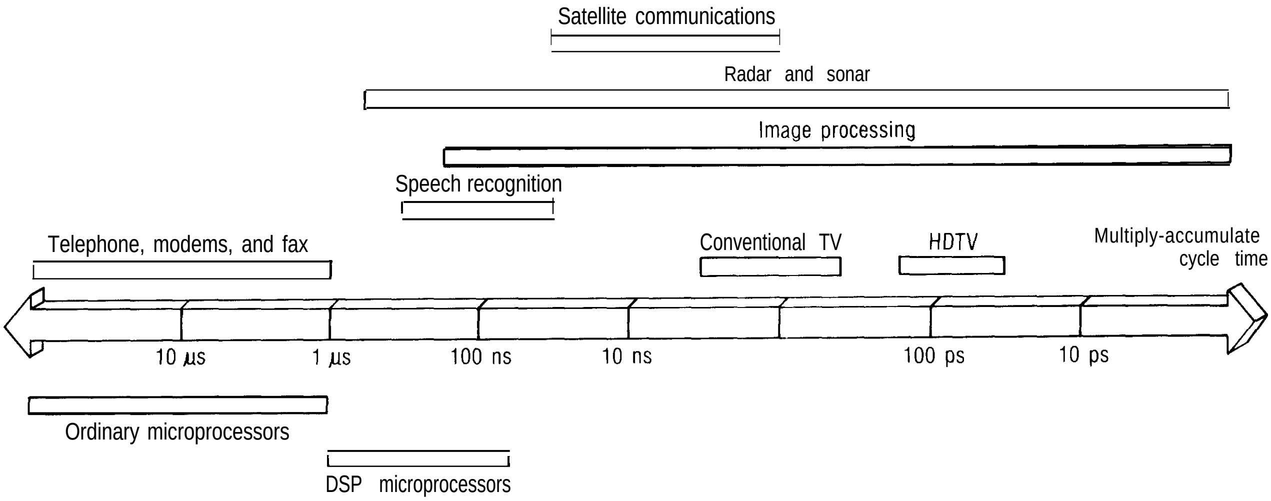
Digital signal processing chips (A/D, DSP, D/A) and digital signal processors in particular for HDTVS are at the leading edge of many aspects of the technology (figure 5-l). For example, at the 1989 International Solid-State Circuits Conference (the most important international conference for unveiling new chip technologies), some of the fastest DSP chips ever developed were specifically designed for

[8]U.S. Congress, Office of Technology Assessment, *Making Things Better: Competing in Manufacturing*, OTA-ITE-443 (Washington, DC: U.S. Government Printing Office, February 1990).

[9]Integrated Circuit Engineering Corp., op. cit., footnote 5.

[10]The development of better video signal compression algorithms is an important non-hardware aspect of current work in HDTV that is also critical to the success of interactive video systems.

Figure 5-1-Selected Applications of Digital Signal Processors v. the Speed of Operation



HDTV is among the most demanding of applications in terms of speed

SOURCE: Jack Shandle, "Signal Processors Open Up New Territory in Communieations," *Electronics*, April 1989, p. 79. Used with permission.

HDTV or related color video signal processing.[11] The only comparably demanding applications today, at least in terms of speed and throughput, are military radar and sonar (highly specialized and low-volume markets), and image processing that is closely related to HDTV.

An uncompressed HDTV signal contains about 1.2 billion bits per second (1.2 Gbps) of information. In comparison, today's advanced engineering workstation hits peak speeds internally of roughly one-half gigabit per second.[12] This signal is compressed, transmitted, and is then converted back into a viewable picture by the receiver. The amount of computation needed to decode this varies with the standard chosen, but can be as much as 2 to 3 billion mathematical operations per second. DSPs are able to handle these huge information flows and computational speeds—roughly comparable to those attained by today's supercomputers—at a cost consumers can pay only through specialized designs tailored for specific tasks. Unlike HDTVS, supercomputers are able to handle a broad range of computations and to do so much more flexibly .13

The development of certain important computer technologies may be aided in part through efforts in developing digital signal processing for HDTV. For example, the "testbeds" built by the Japanese to develop DSPs have required extensive work with massively parallel processor systems—the ability to hook-up many microprocessors in parallel to speed up computations. At Nippon Telephone & Telegraph, for example, the National Academy of Sciences Panel reviewing Japanese HDTV development efforts observed a system with 1024 processors in parallel, far fewer than some U.S. systems but still a notable achievement. Parallel processing has been a significant weakness in Japanese supercomputer technology, and a primary area in which U.S. firms have managed to maintain their edge. The experience with parallel processing hardware that the Japanese have gained in their HDTV development efforts may have spinoffs to their supercomputer systems.

Similarly, HDTV research at the David Sarnoff Research Center has led to the development of a video-supercomputer capable of an information flow rate of 1.4 Gbps and computational speeds of

[11]Richard Doherty, "At ISSCC, Parallel Signal Processing," *Electronic Engineering Times, Feb. 27, 1989.*

[12]Richard McCormack, "Supercomputer Highway Could Be a Country Road, Say Industry Executive, " New *Technology Week,* Aug. 14, 1989.

[13]David Messerschmitt, Department of Electrical Engineering, University of California—Berkeley, personal commm unication, July 31, Oct. 12 and 13, 1989.

[14]Ibid.

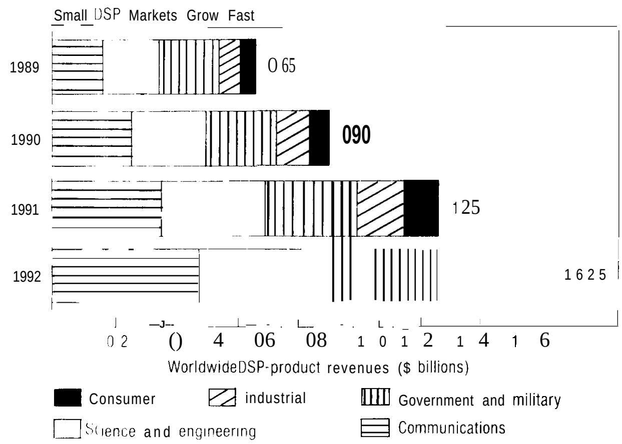
some 1.4 trillion mathematical operations per second at a cost of less than one-tenth that of other supercomputers.[15]

The DSP market is growing rapidly. It is expected to increase from about $650 million per year to $1.6 billion by 1992 (figure 5-2). If the HDTV market develops, HDTVS will use an enormous amount of digital signal processing. For example, the Japanese MUSE-9 system uses some 500,000 gates—a measure of processing power—to convert the highly compressed signal back to a picture.[16] DSP requirements may be less or more than this, however, depending on the eventual choice of transmission and receiver standards.

If high rates of growth are realized for the HDTV market in the United States, Japan, and Europe,[17] then 15 years from now the use of digital signal processing chips in HDTVS alone could be 10 times today's total world demand (measured by processing capacity-' gates") for all microprocessor and related applications and roughly 100 times today's demand for DSP.[18] Such estimates are speculative; their qualifications are discussed below. Depending on the relative growth of the computer, telecommunications, and other markets, this may or may not be important compared to the entire microprocessor and microcontroller market in 15 years. It would, however, almost certainly have a strong impact on the cost of DSPs for video processing. Even under low-growth scenarios a tenth as large, HDTV would likely have a strong impact on the cost of DSPs for video processing.

The United States currently has a stronger position in DSP design than Japan and is about equal to Japan in the production and performance of DSP chips. Domestic firms have managed to maintain a dominant market position in DSP because they have better software for developing these chips. Texas Instruments currently has 60 percent of the world DSP market; NEC is second with 11 percent.[19] Production of DSPs for HDTV could significantly

Figure 5-2—Projected Growth of the Digital Signal Processor Market, 1989-92



SOURCE: Jonah McLeod, "DSP," *Electronics*, April 1989, p. 71.

change these market positions, depending on a firm's presence in HDTV. Such concerns may have been a factor in Texas Instruments' recent decision to purchase the Japanese HDTV chip designs and technology from Japan's NHK in order to participate in the Japanese HDTV market.[20]

DRAMs

HDTVS similarly place heavy requirements on memory technology. Access times needed for HDTV memory chips must be roughly 20 nanoseconds (ns)—20 billionths of a second. Today's fastest DRAMs have typical access times of 60 to 80 ns.

Leading-edge PCs and workstations are providing a significant market pull for the special techniques and faster types of memory devices such as SRAMS (Static Random Access Memory) necessary to operate at high speeds. If the HDTV market develops, it could provide an additional pull for leading-edge fast DRAMs. Matsushita's 8 Mb Video RAM, for example, has a serial access time of 20 ns, 1.5 times faster than current VRAM technology.

[15]David Sarnoff Research Center, "The Princeton Engine: A Video-Supercomputer,' Sarnoff Labs, Sept. 28, 1989.

[16]David Lammers, "U.S. ASICs on TV, " *Electronic Engineering Times*, Feb. 27, 1989.

[17]Corresponding market projections are those by the Electronic Industries Association (EIA) for the United States and the Japanese Ministry of Posts and Telecommunications (MOPT). Similar sales rates were assumed for Europe with appropriate reductions for the observed lower rates of household penetration for color TVs.

[18]World logic Gate production in 1987 is estimated by OTA to be about 2 trillion gates for microprocessors, microcontrollers, and ASICs. The comparison is made by multiplying the high growth projections for HDTV by 500,000 gates per set.

[19]William I. Strauss, "Fe@-Genemtio, DSPs Will Debut Next Year," *Electronic Engineering Times*, Aug. 7, 1989, p. 55.

'Jacob Schlesinger, "Texas Instruments Agrees To Buy HDTV Technology From Japan, " *Wall Street Journal*, Sept. 14, 1989.

HDTV could also become a significant new market for DRAMs. An HDTV might use as much as 32 million bits (Mb), equivalent to 4 million bytes (MB) of DRAM, to store the HDTV picture in memory.[21] Assuming rapid growth of the HDTV market as above, then the use of DRAMs in HDTVS alone in 15 years could be five times the total 1987 world demand (by memory capacity-bits) for all DRAM applications.[22] Depending on the relative growth of the computer, telecommunications, and other markets, this may or may not represent a significant fraction of world DRAM use at that time. Japanese firms are, however, already establishing major new DRAM production facilities with the expectation that their output will be used in Advanced TVs.[23]

These scenarios for DRAMs and DSPS are subject to a number of qualifications and uncertainties. If the standard chosen for HDTV uses significantly lessor more memory and digital signal processing, then the projections would be adjusted accordingly. If the development of the IDTV market, for example, substitutes for HDTV and prevents HDTV market growth, then the DRAM projections would be reduced by a factor of 4 because the typical IDTV is expected to use about a quarter of the memory used in an HDTV.W If consumers instead move progressively upscale, buying IDTVs and EDTVs first and then move to HDTV, relegating their IDTVs/EDTVs to use as a second set as they did B&W sets when moving to color, then chip demands could be 25 to 50 percent greater than projected. If strong commercial markets for HDTV develop, as predicted by the Japanese MPT, then chip demand could be twice the projections above. Factoring in production and broadcasting equipment sales could increase these projections by 10 to 15 percent.[25] Finally, some believe that progressively more sophisticated systems will be developed beyond HDTV, requiring even more memory and signal processing.

Fifteen years ago the United States had more than 90 percent of the world market in DRAMs; today the United States makes less than 15 percent of the DRAMs purchased in world (merchant) markets. Texas Instruments, Micron Technologies, Motorola with technology licensed from Toshiba, and IBM (for internal consumption) are the only U.S. firms still producing DRAMs. The recent effort to forma consortium, U.S. Memories, might have improved somewhat the U.S. position. For a variety of reasons, however, it failed to attract sufficient support from U.S. firms to even be launched.

Gallium Arsenide and Other Compound Semiconductors

Receiver-compatible HDTV systems propose use of the standard 6 MHz NTSC signal, which would then be augmented with a second signal 3 to 6 MHz wide to provide the additional information for the higher quality picture. The wider bandwidth of such HDTV systems may require GaAs (Gallium Arsenide) chips in the tuner due to their wider bandwidth capability and their ability to handle overloads.[26]

GaAs and related materials are now used in a variety of applications, ranging from some leading-edge supercomputers to the lasers in CD-players and in fiber-optic systems. The use of GaAs remains limited, however, due to the difficulty of producing high-quality stock material and fabricating semiconductor devices from it. If HDTV provides a large market for GaAs devices, the additional production volume might help some of these difficulties to be overcome. Improved GaAs materials production and fabrication techniques could have spinoffs to a variety of markets.

The United States seriously lags Japan in a variety of GaAs and related materials, processing, and

[21] Some researchers believe that fairly high resolutions can be achieved without such large use of memory; others insist that there are significant advantages in having a full frame memory, or 20 to 32 Mbits, depending on the standard, etc. Ultimately, the memory and digital signal processor demands will depend strongly on the particular standard chosen, but will also likely increase over time. (A Byte equals 8 bits and can represent one character on a keyboard.)

[22] Estimated 1987 world DRAM production is 2.3×10^{14} bits. Integrated Circuit Engineering Corp., op. cit., footnote 5.

[23] Nihon Kogyo Shimbun, July 6, 1989, cited by Barry Whalen and Mark Eaton, "Prospects for Development of a U.S. HDTV Industry," Committee on Governmental Affairs, U.S. Senate, Hearing 101-226, Aug. 1, 1989, p. 516.

[24] Charles L. Cohen, "NEC Takes An Early Lead in Improved-Definition TV," *Electronics, Dec.* 17, 1987.

[25] William Glenn, Florida Atlantic University, Boca Raton, personal communication, Feb. 10, 1989.

[26] Al Kelsh, National Semiconductor, personal communication, Mar. 21, 1989; Birney Dayton, NVision, personal communication, Mar. 8, @t. 12 and 13, 1989; Ronald Rosenzweig, Testimony at hearings before the House Committee on Science, Space and Technology, Mar. 22, 1989.

device technologies.[27] Despite pioneering the development of many of these semiconductor devices, the United States today buys much of the unprocessed GaAs material from Japan as well as the semiconductor devices fabricated from it. AT&T invented the solid-state laser, but in some cases has purchased semiconductor lasers from Japan to drive its fiber cable.

Semiconductor Manufacturing

Highly disciplined and cost-effective manufacturing is required for a large HDTV market to develop and for a firm to successfully compete within it. Technology will have to squeeze even more circuitry onto the same sliver of silicon to bring the cost of HDTVS to reasonable levels. Reductions of the total number of chips in this manner reduces costs-of components, of assembling and testing the HDTV, of repairing defects, and by increasing reliability. Reducing the number of parts in color TVs was an important aspect of the competition between the U.S. and Japanese producers in the 1970s—and an aspect in which U.S. producers seriously lagged. The quest to reduce the number of chips in systems is responsible for the explosion in ASIC (Application Specific Integrated Circuits) production, which now accounts for about a quarter of all merchant integrated circuit Production.[x]

Efforts to reduce the number of chips needed can already be widely seen in ATV development. NEC, for example, reduced the number of chips in its IDTV from 1,800 to 30.[29] An early prototype of the Japanese MUSE HDTV system had 40 printed circuit boards, each centaining 200 chips for a total of 8,000 chips. In contrast, the latest generation of MUSE decoders unveiled in June 1989 has less than 100 chips. Half of these were ASICs with 26 different designs. To minimize the burden on any one manufacturer in developing these numerous and complex ASIC designs, NHK divided the effort among 6 different manufacturers, and then distributed the designs among all the participants (ch. 2).

Manufacturers are also pushing the design of conventional memory chips. Matsushita recently unveiled an 8 Mb Video RAM designed specifically for application in HDTV, and intends to begin commercial sampling in 1990.[30]

Eventually, nearly all of the required memory and DSP for an HDTV might be combined on a single chip. Increasing levels of chip integration will require a significant increase in current capabilities, and correspond to the expected leading edge of semiconductor technology for the next decade.[31] The extent to which this drives the state-of-the-art will depend on the relative size of the HDTV, computer, telecommunications, and other markets.

A number of important studies have documented the current U.S. lag behind Japan in a broad range of semiconductor process technologies:

- The Federal Interagency Task Force found the United States lagging Japan in 14 semiconductor process and product areas; the United States was ahead in just six categories and its lead was found to be slipping in five of these (figure 1-1).[32]
- The National Academy of Sciences found the Japanese leading in 8 of 11 semiconductor process technologies that will be critical in the future.[33]
- A recent study by the Department of Commerce found Japanese semiconductor plants had a 5-year lead over the United States in the use of computer integrated manufacturing techniques.[34]

27Report of the Federal Interagency Staff working Group, ' 'The Semiconductor Industry, " National Science Foundation, Washington DC, Nov. 16, 1987.

28Merchant producers are those which sell on the open market and include all Japanese and most U.S. semiconductor producers. Captive producers are those which use the semiconductors they produce themselves and do not sell them outside the firm. The world's top three ASIC producers are Fujitsu, Toshiba, and NEC.

29Cohen, op. cit., footnote 24.

30Miyoko Sakurai, "8 Mbit VRAM for HDTV," *Electronic Engineering Times*, Apr. 3, 1989.

31Dayton, op. cit., footnote 26; and* on projections by Craig R. Barrett, "Technology Directions for Integrated Circuits," Seminar at O'IA, June 15, 1989.

32Report of a Federal Interagency Staff Working Group, Op. cit., footnote 27.

33National Research Council, "Advanced Processing of Electronic Materials in the United States and Japan," National Academy Press, 1986.

34W.C. Holton, J. Dussault, D.A. Hodges, C.L. Liu, J.D. Plummer, D.E. Thomas, and B.F. Wu, "Computer Integrated Manufacturing (CIM) and Computer Assisted Design (CAD) for the Semiconductor Industry in Japan," JTECH Panel Report, Department of Commerce, Science Applications International Corp., December 1988.

These techniques have allowed the Japanese to reduce turnaround time by 42 percent, increase unit output by 50 percent, increase equipment uptime by 32 percent, and reduce direct labor requirements by 25 percent.

The Japanese have also rapidly improved their plant and equipment to take advantage of the more technically demanding, but cost-saving, large wafer technology. From a position of parity in 1984, they now use, on average, wafers that are nearly 35 percent larger in area than their American competitors.[35] IBM, however, is pioneering very large, 8-inch, wafer technology.

DISPLAY TECHNOLOGY

HDTV drives display technology perhaps more than any other single area. To truly appreciate HDTV, much larger high-resolution displays are needed than are generally available today. Indeed, some analysts believe that the HDTV market will not take off until large displays—40-inch diagonal and preferably larger-are available at reasonable cost. A HDTV display must have fairly high resolution—lOOO lines or more; superb color; rapid response times; large size; good brightness, contrast, and efficiency; and low cost.

Numerous display technologies are being developed, including: improvements in conventional picture tubes; advanced projection displays using either CRTs, LCDs, or deformable membranes[36]; and large-area flat panel liquid crystal displays, among others.

Conventional picture tubes will undoubtedly continue to be the display of choice over the next few years. They perform well, they are efficient, and they are low in cost due to the many years of experience manufacturing them. In the longer term, however, there will be a shift away from direct view picture tubes. In the larger sizes desired for HDTV, direct-view CRTs are bulky and heavy in addition to being fragile. Although work is being done to reduce their depth[37], CRTs currently are nearly as deep as they are wide-few houses have either doors wide enough to accommodate large CRT displays (40-inch or more) or living rooms large enough to conveniently house them. Furthermore, the weight of a 40-inch CRT display is several hundred pounds.

By the mid-1990s, many analysts expect that high-performance projection systems will be available that provide the larger viewing areas needed for HDTV. Toshiba, NHK, Hitachi, Sanyo, Mitsubishi, and Philips have all developed projection systems for HDTV with screen sizes as large as 50 feet diagonal.[38] LCD and deformable membrane projection systems are also under development with some indications that the deformable membrane may have advantages in efficiency, brightness, contrast, and response time.

By the late 1990s, yet another display technology may become available-the active matrix flat panel liquid crystal display, or AM/LCD. Nine Japanese companies demonstrated 10- to 14-inch color LCD displays with resolutions of 640 by 400 pixels at the 1989 Tokyo Business Show.[39] IBM recently unveiled an experimental high-resolution 14-inch diagonal color liquid crystal display that it co-developed with Toshiba.[40] Figure 5-3 illustrates the current progress in developing AM/LCD displays and a few of the firms that have led the way.[41] The Japanese recently began a 7-year, $100 million collaborative research program to develop very large, 40-inch diagonal, color flat panel AM/LCD displays for HDTV and other applications (ch. 2).

Other display technologies are being investigated, but barring fundamental breakthroughs,[42] they are less likely to be applied to HDTV. (In contrast, for

---

[35]OTA estimate.

[36]CRTs are cathode-ray tubes, the basic technology used today for TV picture tubes.LCDs are liquid crystal displays,the basic technology used today in pocket watches, calculators, and many of the laptop PC displays. Deformable membranes work by reflecting light off a membrane that is deformed point by point to either focus or diffuse the light so as to generate a picture.

[37]David tires, ''Matsushita Flattens CRT,'' *Electronic Engineering Times,* May 29, 1989, p. 29.

[38]Lawrence E. Tannas, "~*TvandHDTVDisplays:* Evolving in Japan,'' JTECH Panel Review of HDTV~Jap~presen~tion at National Academy of Sciences, July 26, 1989.

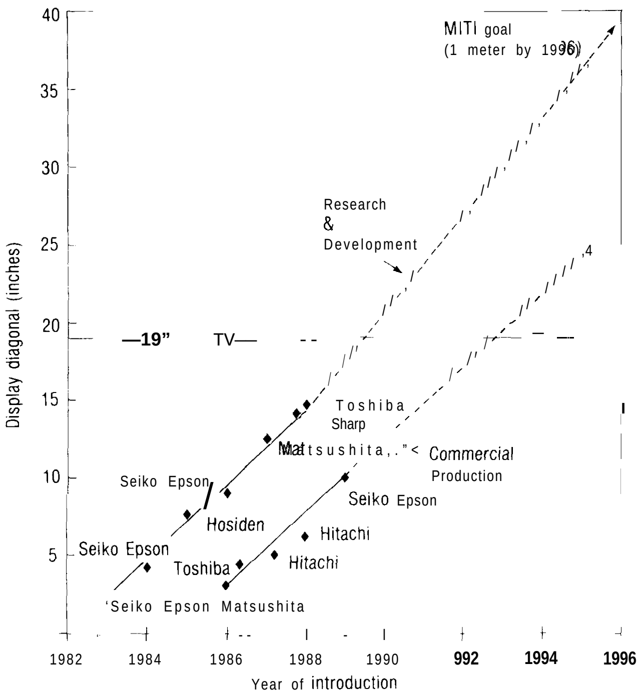
[39]*Electronics,* September 1989, p. 100; Special Advertising Section on Japan.

[40]Ashok Bin@ ''Flat Panel Advances Lead SID,'' *Electronic Engineering Times,* Apr. 24, 1989, p. 35.

[41]William C. Schneider, Griffith L. Resor, ''High-Volume Production of Large Full-Color Liquid-Crystal Displays,'' *Information Display,* February 1989, p. 8.

[42]For example, if a good blue phosphor can be found for electroluminescent displays, they might become a strong competitor with LCDs.

Figure 5-3--' 'Resor's Rule" for Active Matrix Liquid Crystal Displays (AM/LCDs)



This shows the trend in display size by year for displays under R&D and in commercial production. Display size, as measured by the diagonal inch, is increasing at the rate of 3 inches (75mm) per year. Commercial introduction follows R&D production by approximately 3 years.

SOURCE: MRS Technology, Inc., Chelmsford, MA. Used with permission.

flat panel LCD displays the technical limitations are now believed to largely be in engineering.) Among these displays are light-emitting diodes[43], Plasma Display Panels[44], thin-film electroluminescent displays[45], and fiber-optic expanders[46], among others.[47] Size and weight, cost, brightness, power consumption, viewing angle, response time, and manufacturing cost are critical factors for each of these display technologies. Progress in these technologies, however, is being made: the Japanese NHK Laboratory recently announced an experimental 20-inch diagonal plasma display[48], and some believe that new technologies might give plasma displays an edge over AM/LCDs.[49]

Production of large flat-panel displays will require significant advances in a number of important technologies. These include: high-throughput low-cost lithography tools for large area, high-performance patterning of circuitry onto the panel; large-area, high precision glass sheet production; and large-area, high precision thin-film technology.

Such capabilities may have applications in many other areas as well. High precision control of thin films, for example, is generic to a variety of industries, from semiconductors to the production of optical disks. Large-area lithography is expected to be used to develop very high-density printed circuit boards, or "chips on glass" by the Japanese Key Technology Center AM/LCD research consortium. This could be a very important development and is discussed below.

Linkages such as these are difficult to anticipate. Simple accounting may overlook them, but they can sometimes lead to enormous new markets. Consider the example of the Power Integrated Circuit. The Power IC was initially developed and its costs were driven down, in part, by the demands of such devices as plasma and electroluminescent displays, among others,[50] for IC drivers capable of handling medium-level voltages (100 volts instead of the typically 5 or so volts used in computer circuits) and relatively high currents.

[43]LEDs have generally low efficiency in emitting light, and there is an enormous variation in output and efficiency between different colors, making them hard to match. LEDs also have a fairly variable light output from device to device There is relatively little new research going on now in LEDs.

[44]Plasma Display Panels ionize a gas with a medium-level voltage (i.e., 100 volts) causing the gas to glow. Disadvantages include the cost of the electronics to deliver this voltage, low efficiency, and a limited color range.

[45]Electroluminescent Displays work by applying a medium voltage across a material causing it to glow. Limitations are its low efficiency and limited color range. Planar (U.S.), in particular, has been working on developing a better "blue' color as well as better manufacturing processes and electronics that can vary the intensity of the colors. Tom Manuel,"A Full-Color EL Display Is Demonstrated by Planar," *Electronics, May 26, 1988,* p. 73.

[46]Fiber-optic expanders have considerable promise, but are currently embroiled in a patent dispute. See George Gilder, "Severed Heads and Wasted Resources," *Forbes,* June *26, 1989.*

[47]Others include vacuum fluorescent displays, in which Futabe, NEC, and Ise hold the #1, 2, 3 market positions; cold cathode emitter displays; and electrophoretic displays.

[48]Ashok Bindra, ''Flat panel Advances Lead SID, " *Electronic Engineering Times,* Apr. 24, 1989, p. 35.

[49]David Lieberman, ' 'Plasma's HDTV Focus," *Electronic Engineering Times,* June 12, 1989.

[50]Others include nonimpact printers and multiplexing automobile* g, etc. Although applications in automobiles ordy began to be realized much more recently, they were a long-term goal for some manufacturers.

Plasma and electroluminescent displays area tiny fraction of the display market and Power ICs for these panels are a still smaller market. Despite such humble beginnings, Power ICs are now beginning to find applications across a host of industries with important benefits. These range from potentially significant reductions in the weight and cost of aircraft wiring and controls[51] to large improvements in the efficiency of refrigerators, room air-conditioners, and a host of other appliances.[52]

With the expected transition to flat panels and other advanced display technologies, the United States has a fleeting opportunity to regain a strong market position in display technologies. In recent years the United States strength in display technologies and markets has slipped away to the Japanese. The United States still has a few scattered experts in basic CRT technology at Zenith, Tektronix, GE, Raytheon, Corning and a few other fins, but it lacks the broad-based talent of the Japanese, particularly in manufacturing.

U.S. firms are still competitive in some aspects of flat-panel display technologies: in design, in the production of the basic materials, in some of the manufacturing equipment, and in some state-of-the-art displays. Coming makes the best glass substrate in the world for AM/LCD displays and currently holds 90 percent of the Japanese market.[53] MRS Technologies, a Massachusetts venture startup, currently makes the world's best lithography tools for producing large flat panel displays.[54] U.S. firms also held half the 1988 world market in electroluminescent displays compared to Japan's 29 percent; and a quarter of the 1988 world market for plasma displays—down from 57 percent in 1984—compared to Japan's 68 percent.[55]

These strengths are unlikely to last. In AM/LCD displays, there are five significant R&D groups in the United States—Sarnoff Labs, Ovonic, Magnascreen, Xerox, and Philips Labs (Briarcliff).[56] GE recently dropped its research program in LCDs. There are more than a dozen fii in Japan doing R&D in AM/LCD displays, most of them with more projects and people involved than any of the U.S. teams.[57] Tables 5-1 and 5-2 illustrate the disparity between U.S. and Japanese efforts in developing and producing flat-panel displays.

No AM/LCD production lines are now operating in the United States; essentially all of the world's production comes from Japan-which holds roughly 96 percent of the world market for (small pixel) passive matrix LCDs and virtually IOOpercent of the market for active matrix LCDs.[58] Even if the United States were to make breakthroughs, the manufacturing infrastructure to produce the displays would not be in place. Without production, there will likely be little revenue to continue a long high-level research program-particularly considering the large capital investment and engineering effort required for producing very large area screens.

Already, the remaining U.S. strengths are being challenged. For example, a MITI-sponsored consortium, the New Glass Forum, was begun in 1985 to do R&D in glasses, some of which may have applications to AM/LCDs. Nikon (Japan) recently announced a lithography system with a higher throughput than that of MRS Technologies.[59]

The market for displays for all purposes is large. Worldwide sales of flat panel displays of all types was $2.4 billion in 1988, out of a total display market of $8.2 billion. The flat panel market is expected to approach $6.3 billion by 1995, out of a total display market of $14 billion.[60] Other estimates place the

---

51 Vladimir Rumennik, "power Devices Are In The Chips," *ZEEE Spectrum*, July 1985.

52 Samuel F. Baldwin, "Energy-Efficient Electric Motor Drive Systems, " in *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications*, *Thomas* B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.) (Lund, Sweden: Lund University Press, 1989).

53 Gary Stix, "~n~ac~g Hurdles Challenge Large-LCD Developers, ' *IEEE Spectrum*, September 1989, p. 40.

54 Note, however, that it has lower throughput than the recent Nikon offering. See Stix, op. cit., footnote 53.

55 Heidi Hoffman, U.S. Department of Commerce, personal communication, Nov. 29, 1989.

56 Griffith Resor, MRS Technologies, personal communication, Oct. 12, 1989.

57 Lawrence Tannas, Tannas Electronics, personal communication, Aug 9, 1989.

58 Bob Whiskin, BIS Mackintosh, London, personal communication, Mar. 29, 1989.

59 Stix, op. cit., footnote 53.

60 "U.S. Brains for a Desperate Fight in Flat Panels," *Electronics*, December 1988.

Table 5-1—Status of U.S. Producers of Flat Panel Displays in the 1980s

Company	EL	LCD	PDP	Other
Alphasil		Closed 1988		
AT&T			Closed 1987	
Cherry	Production			
Coloray				Seeking funding
Control Data			Closed 1980	
Crystal Vision		Closed 1984		
Electro-Plasma			Production	
EPID/Exxon				Closed 1986
Kylex/Exxon		Sold 1983		
GE		Sold 1989		
GTE	Closed 1987			
IBM			Sold 1987	
LC Systems		Closed 1988		
Magnascreen		Research		
NCR			Closed 1984	
Ovonic		Research		
Panelvision		Sold 1986		
Photonics			Production	
Planar	Production			
Plasma Graphics			Closed 1985	
Plasmaco			Research/Prod.	
Sarnoff Labs		Research		
Sigmatron Nova	Closed 1988			
TI			Closed 1983	
Xerox		Research		

SOURCE: Dave Mentley, Stanford Resources, Inc., San Jose, CA, personal communication, Apr. 25,1990;JimHurd, Planar Systems, Inc. Portland, OR, personal communication, May 1, 1990; Larry Weber, Plasmaco, Highland, NY, personal communication, May 1, 1990; and Defense Science Board, "High Definition Systems Task Force, Final Report," Washington, DC, forthcoming.

Table 5-2—Recent Investments in AM/LCD Production Facilities in Japan

Company	Investment (U.S. $million)[a]	Operational	Factory location	Technology
Alps	$33	1992	Iwaki	TFT
Fuji-Xerox	80	ND	Ebina	a-Si TFT
Hitachi	134+67/yr	ND	Mobara	a-Si TFT
Matsushita	230	4Q1991	Osaka	Poly-Si TFT
NEC	67	ND	Kagoshima	TFT
Seiko Epson	167	ND	Nagano Pref.	TFT
Seiko Instruments	20	ND	Akita Pref.	Diode Matrix
Sharp	447	3Q1993	Tenrie/Mie	a-Si TFT
Toshiba/IBM-J	134	2Q1991	Himeji	a-Si TFT

[a]Converted at U.S.$1=150 Yen.

KEY: TIT-thin fiim transistor; a-Si—amorphous-silicon; Poly-Si—poly-silicon

SOURCE: Dave Mentley, Stanford Resources, Inc., San Jose, CA, personal communication, Apr. 25, 1990; and Defense Science Board, "High Definition Systems Task Force, Final Report," Washington, DC, forthcoming.

flat panel market as high as $11.7 billion by 1996.[61] The display market is also primarily driven by consumer applications: 70 percent of the 1988 market was for consumer electronics; just 18 percent for computer applications.[62]

The market for displays for HDTV could also be large. For example, if AM/LCDs became the display of choice, using the high-growth scenario above, screen production for HDTV would be nearly 6,000 times total world production of active matrix LCD

[61]David Lieberman, "Colorful Future for Flat panels," *Electronic Engineering Times*, Jan. 8, 1990, p. 71.

[62]Edmond Branger, "Flat Panels *in Focus*, "*Electronic Engineering Times*, Mar. *20, 1989.*

screens today.[63] HDTV might then be an important driver of flat panel display technology as well as contributing to economies of scale in production. Even with a small market for HDTV, the special requirements of HDTV will drive large-area AM/ LCD or other flat panel technology development.

STORAGE

The state-of-the-art in magnetic and optical storage technologies for studio use is already being pushed by the large volume and high rate of information flow requirements for HDTV and, to a lesser extent, related HRS.[64] Digital VCRs for studios will require much higher magnetic recording densities and information transfer rates through the use of improved magnetic materials, recording heads, and other techniques.[65] Sony, for example, has developed a prototype studio VCR that has a recording speed of 1.2 Gbps—five times faster than the previous record.[66] To similarly extend recording times on compact disks, the semiconductor lasers used will have to operate at higher frequencies than those used today, requiring advances in semiconductor lasers and reductions in production costs.[67] Matsushita has recently succeeded in storing 2.6 GB of video information on a single 12-inch optical disk.[68] These recording technologies will have many applications in the computer industry.[69]

Such spinoffs from consumer electronics have already been widely seen. Magnetic and optical (compact disks) storage technologies were both originally developed for the consumer electronics market, but are now used widely in the computer industry. In particular, compact disks are expected to have a profound impact on information handling generally.

Similarly, Digital Audio Tape (DAT) drives, originally developed for the consumer market, are expected to have a significant impact on the computer data storage market. DAT sales in the U.S. consumer market have been limited due to U. S.-Japan trade friction and issues of copyright protection; therefore, prices are expected to remain higher than if large volume sales had already been achieved. If approved, legislation currently pending in the Congress that requires copy-controlling devices in DAT machines may open up U.S. markets. DAT will be able to store about 1.3 GB of data on a cassette the size of a credit card and about 3/8-inch thick and will have data rates of roughly 1.4 Mbps.[70]

There are also spinoffs between technologies. The hard drives used in computers are made by coating a very thin, high-quality layer of magnetic material on a metal disk. The technology to do this, and even the processing equipment, originally came from semiconductor wafer fabrication. A key technology for large-area, flat-panel displays will similarly be putting extremely thin, high-precision coatings over very wide areas. Once developed, this could have an impact on the production of semiconductors, and on magnetic and optical storage. The converse is also true. Thin-film technologies developed for the semiconductor industry could initially have an impact on flat panel production, although the impacts will likely decrease as the panel areas increase.

[63] World total production of small pixel (not watches or calculators) passive LCD displays in 1988 was roughly 6.13 million units, of which Japanese firms produced 96 percent, U.S. firms 4 percent. World production of active matrix displays was 0.21 million units in 1988, essentially all Japanese firms. Assuming a distribution of 60 percent, 3- to 6-inch diagonal, and 40 percent, 6- to 12-inch diagonal and averaging, the area is approxirnately 4.6 million square inches of active matrix panels; and 135 million square inches of passive matrix LCDs. If high growth rate projections are realized, assuming each HDTV has a 40-inch diagonal (or 768 square inches for a 16:9 aspect ratio), then the total active matrix screen area produced will be 5,844 times today's production of active matrix screens; 200 times today's production of passive matrix. For the large areas required for HDTV, active matrix screens will be necessary. World LCD production figures for 1988 were supplied by Bob Whiskin, BIS Mackintosh, London.

[64] Note that for consumer use, the extensive signal compression brings storage densities to near the level of current technology, which is doubling its storage capacity every 2.5 years. The video signal is not compressed before storage in the studio, however, to prevent the introduction of errors or artifacts.

[65] Others might include improved error correction algorithms or data coding techniques.

[66] "HDTV Faces Many Hurdles in Japan," *Electronic Engineering Times*, Apr. 10, 1989. And Messerschmitt, op. cit, footnote 13.

[67] "HDTV Faces Many Hurdles in Japan," op. cit., footnote 66. Increasing information storage on today's CDs is difficult because the spot size on the CD is approaching the wavelength of the lasers used-the system is approaching the diffraction limit. To increase data storage, higher frequencies are needed.

[68] "Digital HDTV Goes On Record," *ZEEE Spectrum*, September 1988, p. 26. Please note that gigabytes (GB) is a volume of information-like a bucket of water; whereas gigabits per second (Gbps) is a rate of information flow—like the rate of flow through a hose. These cannot be compared.

[69] "Archives in Miniature," *PC* Magazine, Jan. 31, 1989.

[70] Terry Costlow, "TechDiscord Rips Tape Industry," *Electronic Engineering Times, May 29, 1989*, p. 53; Eng Tan and Bert Vermeulen, "Digital Audio Tape for Data Storage," *IEEE Spectrum*, October 1989, p. 34.

Precision motors like those used in HD-VCRS will also be used in computer tape and disk drives, robotics, and elsewhere. Today, Japan is the world's largest producer of precision motors due to this synergy of uses among electronic products.[71]

The high-precision helical scan drives for VCRs are now made primarily in Japan, although a few are made in Korea. Exabyte of Boulder, Colorado purchases off-the-shelf 8mm camcorder-type tape drive mechanisms from Sony and uses them in a 2.3 GB tape system (the highest storage capacity to date) for computer data storage;[72] they are totally dependent on the Japanese source. With the continuing move to higher density storage systems, firms that produce computer tape storage systems, but do not have access to helical scanning (VCR-type) tape drives are unlikely to survive.[73]

The United States continues to hold a strong R&D and market position in some storage technologies, but has seriously lost ground in others. The United States has largely lost the floppy drive business, holding just 2 percent of world sales in 1987; but in the hard drive market, U.S. firms have fought back successfully and still hold a 60 percent or better share. 3M continues to be a major world-class producer of magnetic tape; but no U.S. firm produces the high-performance helical scan recorder drives. Only one domestic firm, Recording Physics in California, has the capability to produce the very high-performance materials needed for read/write VCR heads.[74]

The United States lags in many areas of optical storage research, and has little presence in the manufacture of optical storage devices. Over a dozen Japanese firms are developing or selling advanced rewritable optical disks and/or drives.[75] The optical data storage device market is expected to grow from $400 million in the United States in 1988 to $7.3 billion by 1993.[76]

COMMUNICATIONS

With the declining costs of fiber, the extension of fiber to the home is expected to become more affordable. Some estimate fiber may be cost-effective for large, new housing developments by 1992. There are optimistic projections that 17 million homes and small businesses could be hooked up to fiber by 1999.[77] The very high information carrying capacity of fiber may make it the carrier of choice for HDTV in the future; and if the HDTV market develops, it could further stimulate the use of fiber-initially in the cable backbone and later to the home.[78] In the near- to mid-term, however, coaxial cable will continue to be the most important medium for carrying video signals to the home.[79]

As HDTV begins to be networked via fiber-optic, it could be an important force behind the next generation of telecommunications equipment. HDTV will require wide bandwidths and, correspondingly, a wide bandwidth switching and control system at a cost consumers will pay (figure 5-4). Similarly, low-cost techniques will have to be developed for installing optical fibers to households. Software to operate and manage a fiber network must also be developed. Today, software is a significant fraction of the expense of telecommunications[80] and recent

[71] Yuji Akiyama, "Growing Demands of Precision Motors Are Supported by AV Equipment, Industrial Robots," *JEE*, February 1986, pp. 30-35. In particular, he notes that 40 percent of Japan's precision motors go to audio video equipment. Further, fewer than 10 producers in Japan are able to make motors of the precision needed for home VCRs, with a core deviation of less than 2 microns, a speed deviation of less than 0.02 percent and a price less than 1,500 yen.

[72] Please note that this is the standard VCR tape drive as used by consumers today. Its recording capacity is in GBytes and cannot be compared to the experimental Sony HDTV studio tape drive above with a recording speed of 1.2Gbits per second.

[73] Clark Johnson, Consultant, personal communication, Aug. 11, 1989; Oct. 26, 1989.

[74] Ibid.

[75] These include Sony, Sharp, Canon, Nikon, Olympus, Matsushita, Toshiba, Mitsubishi, Hitachi, Fujitsu, NEC, Ricoh, Pioneer. *Electronics*, September 1989, Special Advertising Section on Japan, p. 105. Roughly one-sixth of optical disk drive production for computer data storage applications, on a $-basis, is done in the United States but essentially none for consumer applications is made here, and this is a far larger market today. Ron Powell, NIST, personal communication, Nov. 14, 1989.

[76] Manny Fernandez, "Forecast '89-Mixed Emotions," *Electronic Engineering Times*, June 12, 1989.

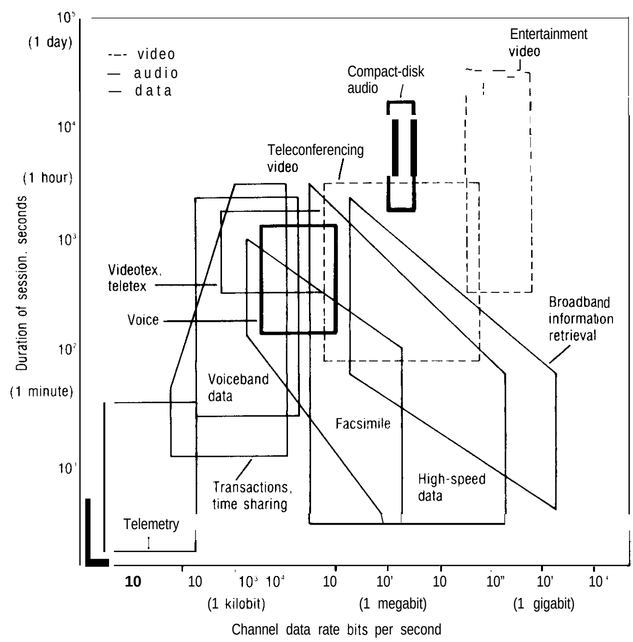
"'Fiber Optics: Getting Cheap Enough To Start Rewiring America," *Business Week*, July 31, 1989, p. 86.

[78] Larry Wailer, "Fiber's New Battleground: Closing the Local Loop," *Electronics*, February 1989, p. 94.

[79] Terrestrial broadcasting, of course, is the second most important in terms of household access and will continue to serve a very important role. Whether delivered by cable or terrestrial broadcasting, the three major networks are the most important source of programming.

[80] Jules Bellisio, Bellcore, personal communication, Mar. 15, 1989.

Figure 5-4-Data Transmission Rates and Holding Times for Different Types of Data Communications



High-resolution video is among the most demanding of applications in terms of channel data rates, and also requires long holding times.

SOURCE: Stephen B. Weinstein, "Telecommunications in the Coming Decades," *IEEE Spectrum*, November 1987, p. 62. Used with permission.

failures in the telephone system caused by software suggest that additional development may be needed.

Consumer electronics has already had an enormous impact on opto-electronics. Much of the leading research in solid-state lasers has been, for example, by the companies that produce compact disk players. (Related high-performance solid-state lasers power fiber-optic networks.) These revenues have in turn provided the capacity to further advance the state-of-the-art.[81]

Despite pioneering fiber-optics and the electronics that drive signals through the fibers, the United States now lags Japan in many aspects of R&D and the production of fiber and associated electronic components. The United States still leads Japan, however, in linking these components together into complete communications systems.[82]

PACKAGING/INTERCONNECT

Packaging/Interconnect (P/1) is the set of technologies that connect all of these components—semiconductors, displays, storage, and communications-into fictional systems. To connect a silicon chip to the outside world, the chip is mounted in a plastic or ceramic package that has tens to hundreds of metal leads. These packaged chips are mounted on printed circuit boards which, in turn, are interconnected via standard multipin connectors on a motherboard or a backplane (figure 5-5).

The cost of these connections increases rapidly at each level. Within the chip itself there are millions of tiny wires of aluminurn connecting the transistors formed in the silicon. Despite their complexity, these connections typically cost just $0.0000001 each because they are all formed in a single step using a photomask. The cost of the connections between the chip and the package it is mounted on are roughly $0.01. The cost of connections between the package and the printed circuit board are roughly $0.10 each. And the cost of connecting the printed circuit board to the backplane are roughly $1.00 each.[83] Overall, the cost of packaging/interconnecting and assembling the electronic components, together with testing the system, accounts for roughly 30 to 50 percent of the total for a complex electronic system. Most system reliability problems are due to interconnect failures, and P/I technologies are a principal barrier today to achieving higher system performance.

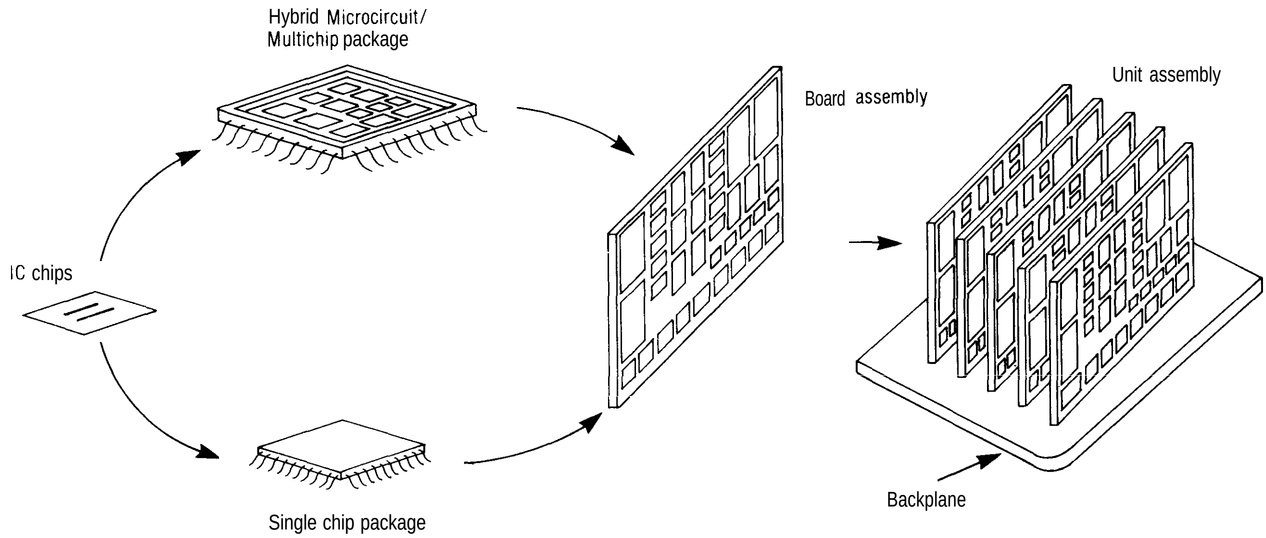
Today's printed circuit board technology, for example, etches individual circuit patterns in copper foil laminated to sheets of fiberglass-reinforced epoxy. Multiple layers of unique circuit patterns can be laminated together with more epoxy. Packaged semiconductors and other components are then mounted on the board and interconnected via copper-plated holes to specific circuit patterns on different layers of the board. These holes account for a large fraction of the total board area and limit wiring densities and component spacing, and thus slow attainable system speeds while increasing system size, weight, and costs. The mechanical drilling process used to form these holes limits further reductions in their size.

[81] James J. Tietjen, David Sarnoff Research Center, Testimony before the Senate Committee on Governmental Affairs, Aug. 1, 1989.

[82] "Assessing Japan's Role in Telecommunications," *IEEE Spectrum*, June 1986.

[83] John S. Mayo, "Materials for Information and Communication," *Scientific American*, October 1986, p. 61.

Figure 5-5-Levels of Packaging/Interconnect



Transistors are interconnected via metal leads on the integrated circuit and is then mounted in a plastic or ceramic package. The packaged integrated circuit is mounted on a printed circuit board which, in turn, is mounted on a motherboard or a backplane.

SOURCE: Adapted from: National Security Industrial Association, Electronics Packaging/Intereonneet Task Force, "Electronics Packaging/Intereonneet: The Next Crisis for Cost-Effective Military Electronics," Washington, DC, draft, 1989.

As an example, interconnecting the 200 *or so* chips of a supercomputer processor, each chip having 250 input/output leads or more, would require a board with 40 layers of circuitry.[84] Advanced ICS may require 500 to 1,000 inches of interconnect wiring per square inch of board-two to three times the current practical limit. Designing and building such boards reliably is very difficult.

Small, high-density multichip modules are one means of improving P/I performance that is now gaining favor.[85] IBM's 3090 mainframe, for example, combines many chips in a ceramic module with 44 layers of wiring. These modules are then mounted and interconnected via a printed circuit board with relatively few layers.

In the longer term, the Japanese MITI and Key Technology Center flat-panel display consortium (ch. 2) intends to use the lithography and thin-film technologies developed for large-area flat panel displays to advance these printed circuit board densities through improved and lower-cost 'Chip-on-Glass" technologies.

Chip-On-Glass technology mounts "bare" integrated circuits directly on lithographically printed glass substrates. This has several important advantages. Fine-line lithographic printing can provide perhaps ten times the wiring density attainable with the conventional copper-epoxy printed circuit boards described above. Increasing the wiring density also reduces the number of layers necessary. This reduces the space that must be allotted to the interconnections between layers. The savings are multiplicative. A conventional printed circuit board with 40 layers of copper-epoxy interconnect might be replaced with a lithographically printed glass substrate with just two layers of interconnect.[86] This provides substantial cost savings in both design and production.[87]

Mounting the bare IC directly on the substrate bypasses several conventional packaging and interconnect steps with further corresponding cost savings and improvements in reliability. Together, the higher wiring density and use of bare chips can allow substantial increases in how close components are

[84]Samuel Weber, "For VLSI, Multichip Modules May Become the Packages Of Choice, " *Electronics,* April 1989, p. 106. This is roughly equivalent to a Fujitsu supercomputer.

[85]Ibid.

[86]Typically, a total of five layers might be needed: one for bonding pads for the chips, two for interconnect, one for power, and one for ground.

[87]Barry Whalen, MCC, personal communication, May 12, Oct. 12 and 13, 1989; Jan. 23, 1990.

packed. This allows higher speeds and reduces system size and weight.

Chip-On-Glass technologies are used in special, high-performance cases today, but could be applied much more widely if large area lithography tools and related technologies were available. These techniques would allow many glass substrates to be produced at once on a large sheet, rather than tediously one-at-a-time.

The complexity and high speed of the chips used for HDTV will require the use of high-performance printed circuit boards. Complex multilayer printed circuit boards will be necessary and new materials may have to be developed to handle the high speeds at an affordable cost.[88] Although these are all available today in high-end commercial and military markets, manufacturing in volume for the HDTV market might force rapid improvements in production technology and dramatically lower their price.

The United States seriously lags Japan in many of these P/I and related assembly technologies. A recent National Academy of Sciences study found the majority of U.S. companies 4 to 5 years behind Japanese competitors in manufacturing process control and in factory automation for fabricating, assembling, and testing electronics products.[89] The United States also lags Japan and Europe in the use of surface-mount technology for connecting the chip to the printed circuit board (figure 5-6).[90] This technology saves space, increases reliability and performance, and reduces assembly costs. Tape Automated Bonding (TAB) technologies for packaging semiconductors, invented in the United States by GE but used more widely in Japan, offer significant increases in reliability at greatly reduced labor and cost.[91] In addition, TAB significantly improves semiconductor Performance.[92]

Producing P/I equipment and materials for HDTV or, more generally, for the flat-panel display market may provide economies of scale to a firm as well. Shindo Denshi, the largest Japanese producer of TAB tape, currently gets half of its sales from supplying producers of LCD displays. Some Japanese companies, such as Toshiba and Matsushita, have also developed proprietary "outer lead bonders" for connecting wires to the display. This technology is not for sale and might make it more difficult for U.S. firms to enter the market.[93]

Many P/I and related technologies—assembly, test, surface-mount, tape-automated bonding-have been pushed the hardest by the consumer electronics market. The Sony Watchman television, for example, uses higher performance TAB than the NEC SX-2 supercomputer.[94] The consumer electronics market demands high reliability, small size, and low cost, but at the same time provides very large volume markets that allow even expensive, yet innovative, technologies to pay for themselves through long-term productivity improvements as experience is gained.

Because of these characteristics, consumer electronics often pushes the state-of-the-art in manufacturing technologies harder than lower-volume but higher-profit markets-especially for assembling components or systems. If the HDTV market develops, it may similarly provide manufacturers a testing ground for developing new assembly technologies with the volume needed to pay for themselves, as well as gaining valuable experience in assembly of sophisticated electronic systems that can be transferred to many other products.

[88] Jack Fuhrer, Sarnoff Labs, personal communication, Mar. 15 and 20, 1989; Dayton, op. cit., footnote 26. At the very high expected processing speeds, better PC board material maybe needed than standard epoxy as it is too absorptive at these high frequencies. Teflon boards have desirable dielectric properties and are now used in high-speed computers, but will be too expensive for the consumer market. It may be necessary to develop new materials that: are low-loss dielectrics; have good temperature characteristics; and bond well to copper. Alternatively, some labs are trying to avoid these high speeds on the board itself, which would require higher quality materials, by putting bus speed multipliers on each chip and thus running at the higher speeds only within the chip itself.

[89] Manufacturing Studies Bored, "The Future of Electronics Assembly: Report of the Panel on Strategic Electronics Manufacturing Technologies" (Washington, DC: National Academy Press, 1988),

[90] Wesley R. Iverson, "Surface-Mount Technology Catches On With U.S. Equipment Makers-Finally," *Electronics*, December 1988.

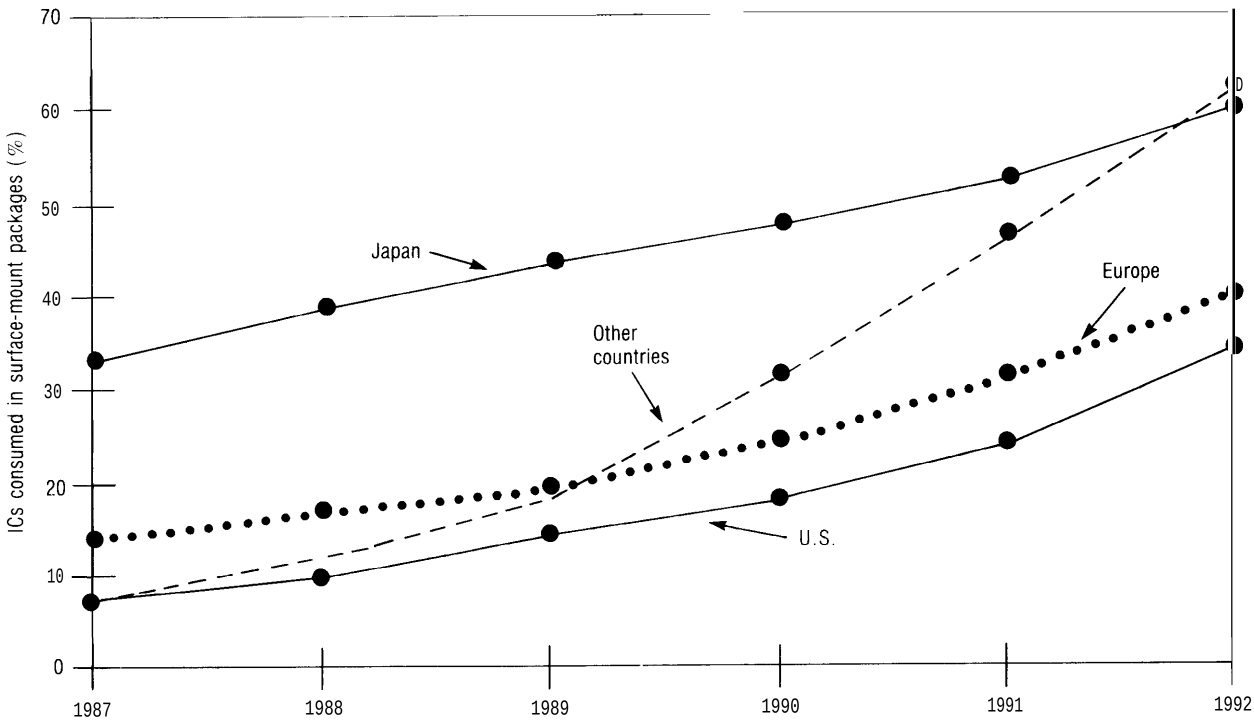
[91] Jerry Lyman, "Is Tom Angelucci's Big Gamble Finally Paying Off?" *Electronics*, Feb. 17, 1986; "NEPCON Highlights the Dominant Role Tape-Automated Bonding Is Taking," *Electronics*, Feb. 18.1988. David Lammers and Ashok Bindra, "Tape Automated Bonding Sparks Renewed Interest," *Electronic Engineering Times*, July 10, 1989, p. 53.

[92] Pieter Burggraaf, "TAB for High I/O and High Speed," *Semiconductor International*, June 1988.

[93] James G. Parker and E. Jan Vardaman, "HDTV Developments in Japan," TechSearch International, Inc., Austin, TX, 1989.

[94] "The Future of Electronics Assembly," op. cit. footnote 89.

Figure 5-6-Fraction of Integrated Circuits Used in Surface-Mount Packages for Japan, Europe, and the United States



SOURCE: Wesley R. Iverson, "Surface-Mount Technology Catches On With U.S. Equipment Makers—Finally," *Electronics,* December 1966, p. 116. Used with permission.