

Silicon Mountain DRAM

Building the World's Fastest PCs

David Bondurant, Retired PE

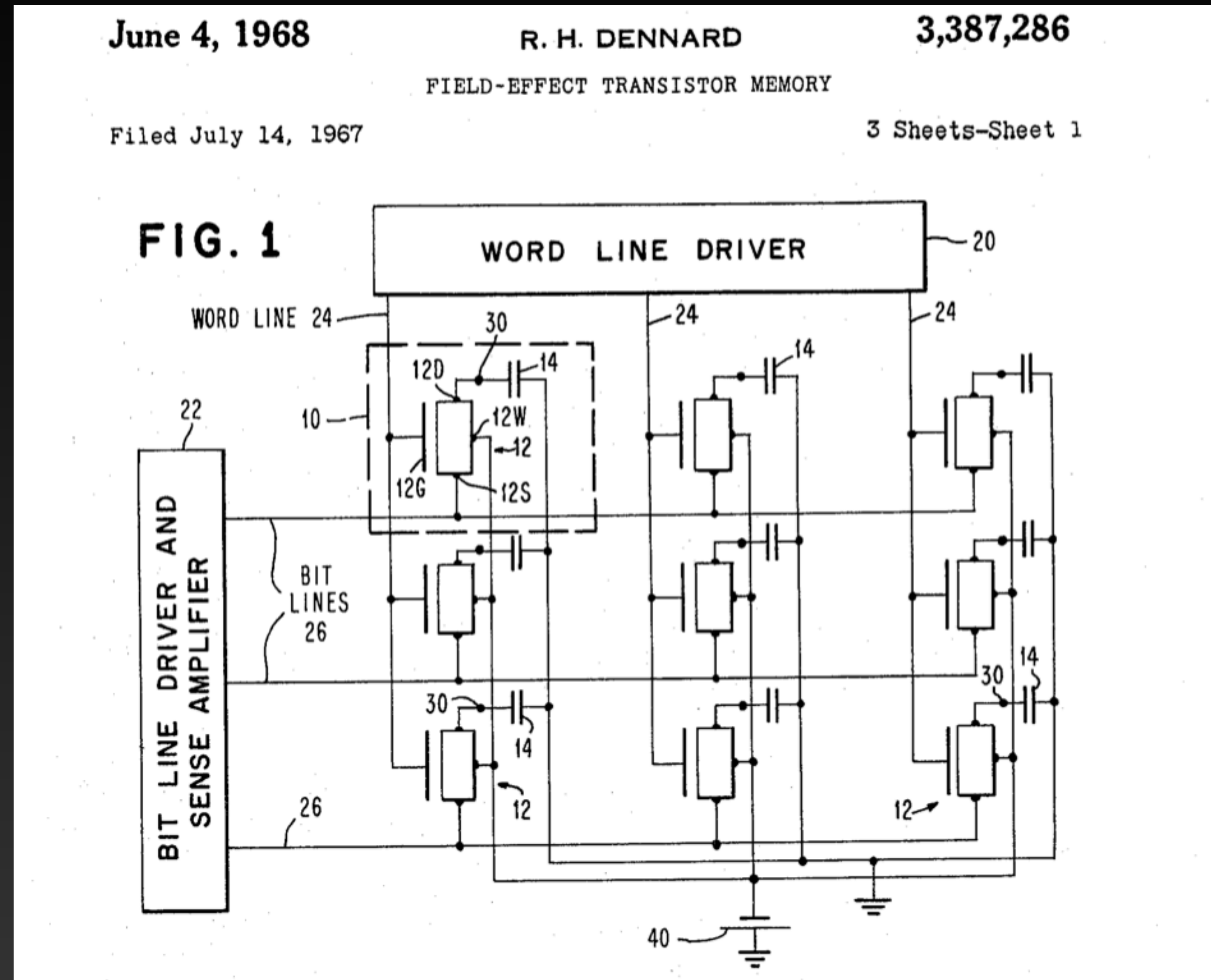
Pikes Peak Life Member Affinity Group Chairman

Former VP of Marketing & Applications, Enhanced Memory Systems

History of the DRAM

Creating The New Main Memory

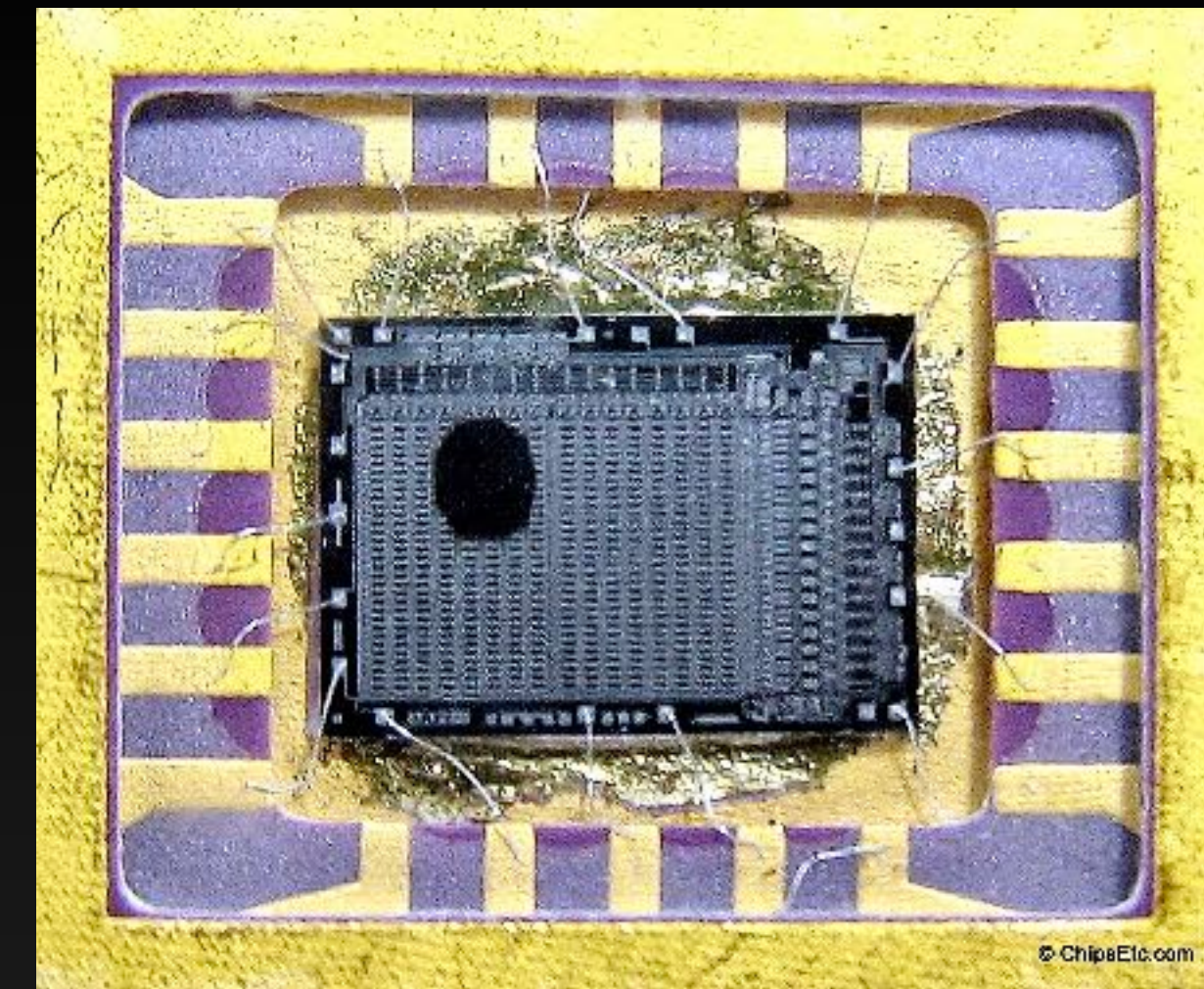
- Dynamic Random Access Memory (DRAM) was used on code breaking computers at Betchley Park UK during WWII using Tubes and Capacitors
- Magnetic Core Became the Main Memory for computer during 1950s and 1960s
- Dr. Robert Dennard of IBM Research patented the first semiconductor DRAM in 1968



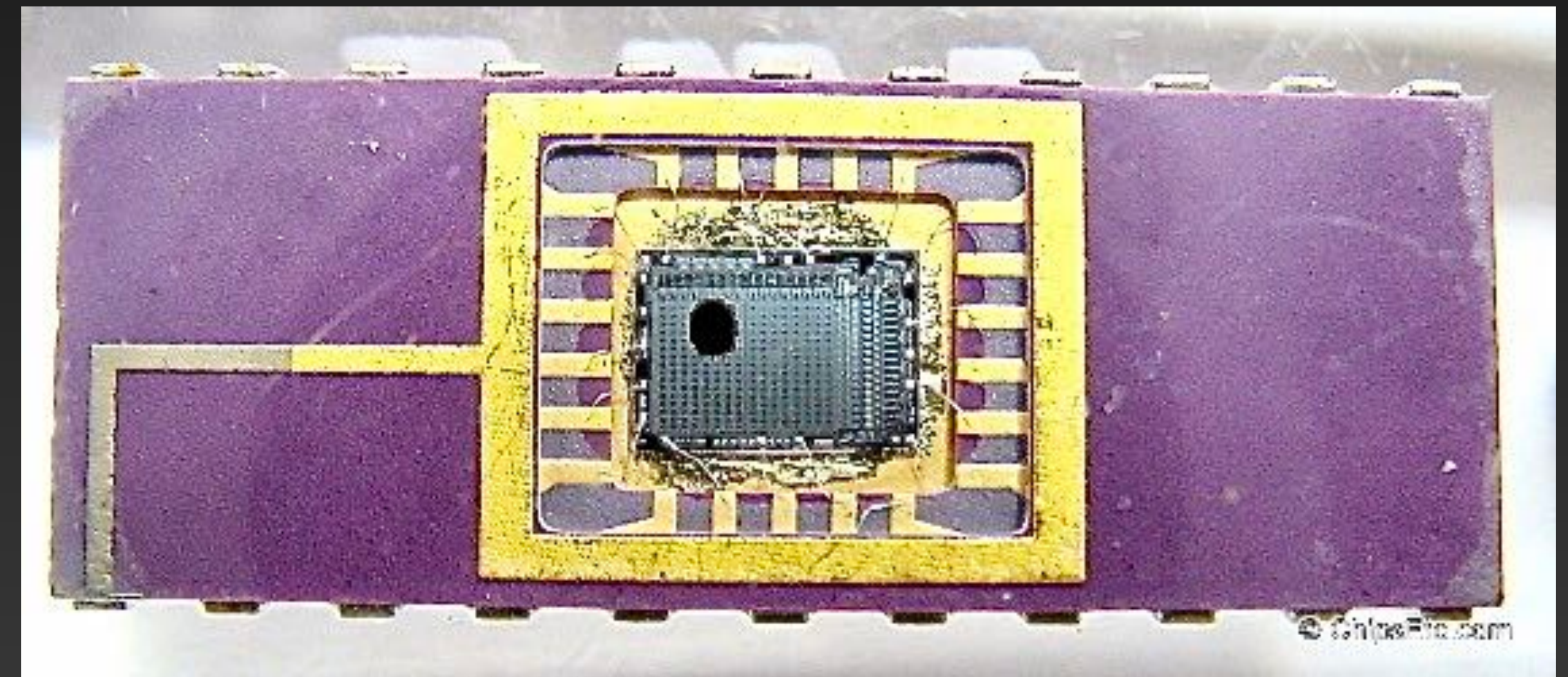
History of the DRAM

Creating The New Main Memory

- Advanced Memory System (AMS) in Sunnyvale produced The First Monolithic 1Kbit DRAM in 1969
- AMS Founders were D. Berding(IBM), R. Lloyd (IBM), B. Dickson (Motorola), J. Larkin(Fairchild), and C. Fa (Collins Radio)



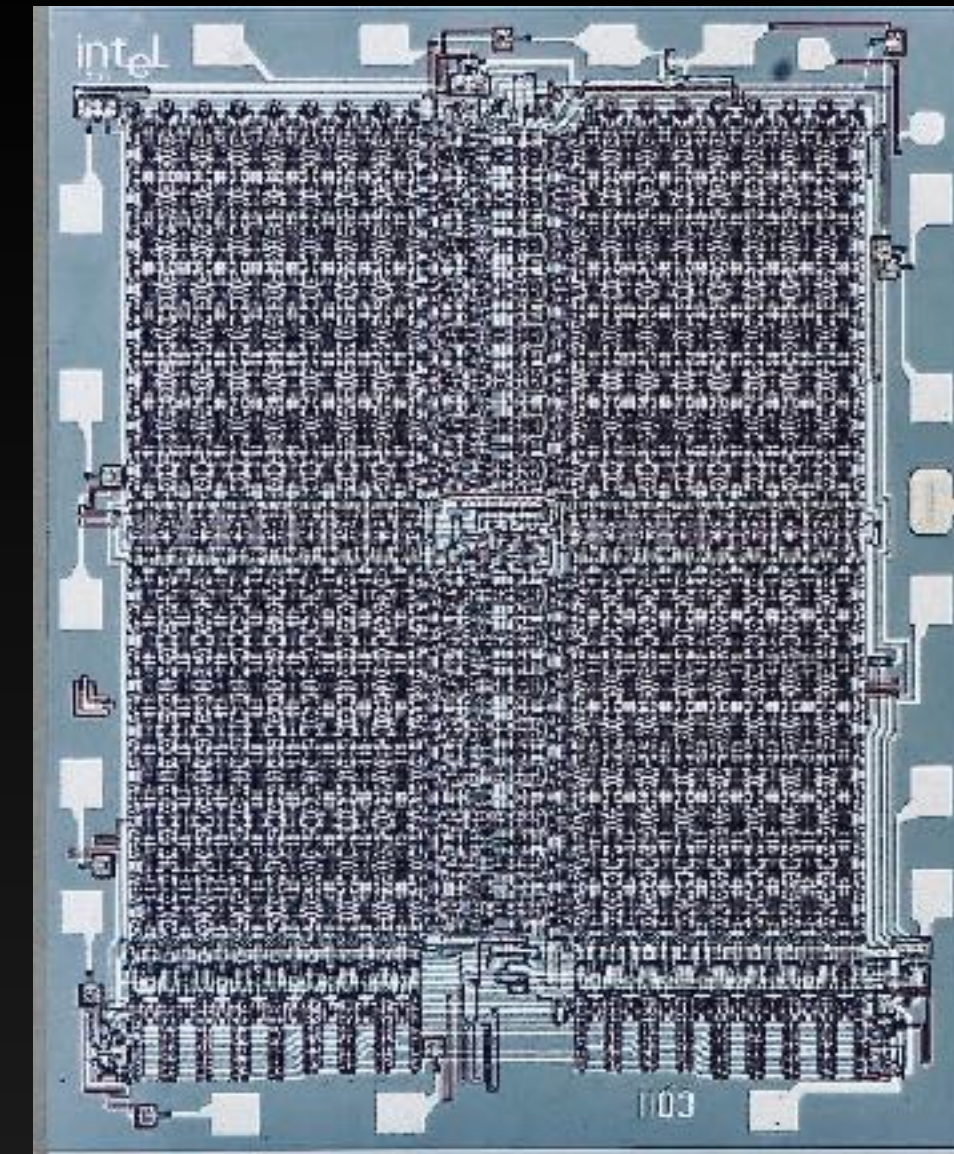
AMS 7001 1K DRAM



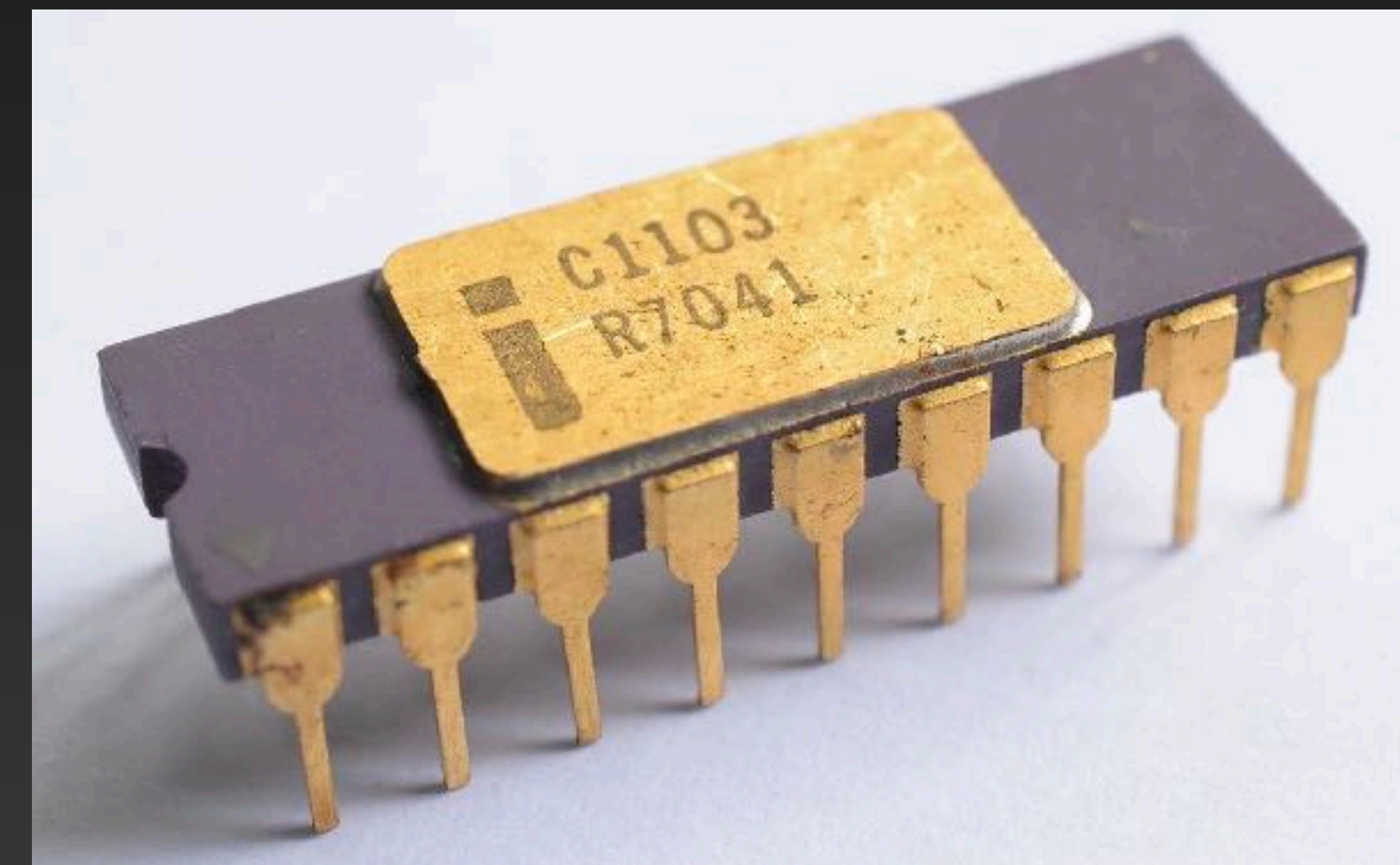
History of the DRAM

Creating The New Main Memory

- Honeywell worked with Intel Corporation to produce the first Commercially Successful 1Kbit DRAM - 1103
- By the early 1970s, Intel's 1103 had replaced core memory
- Intel's DRAM became the world's highest volume semiconductor product



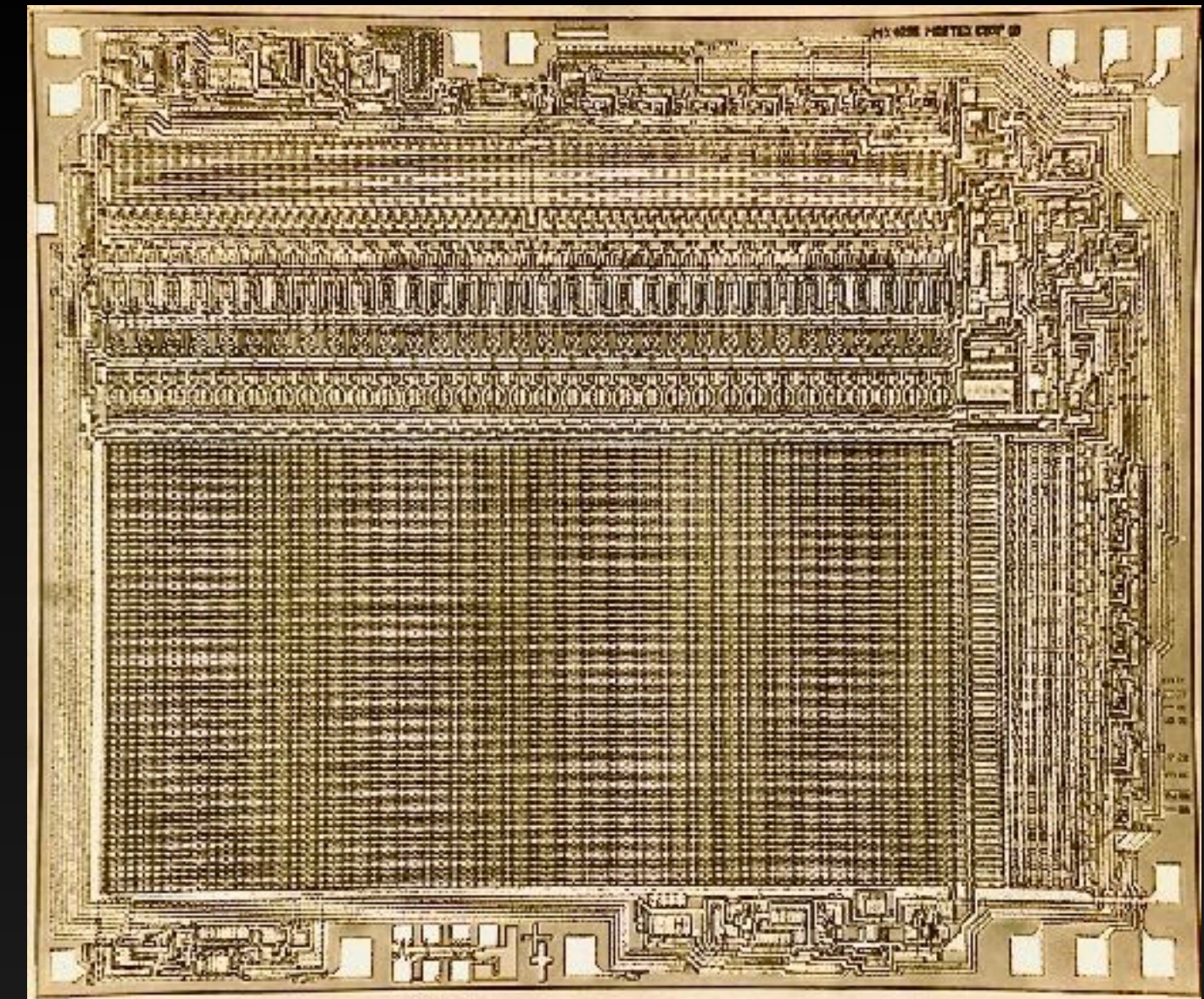
Intel 1103 1Kbit DRAM



History of the DRAM

Creating The New Main Memory

- Mostek was founded in 1969 in Carrollton, TX
- Founders were LJ Sevin, Dr. Richard Petritz from Texas Instruments
- Bob Proebsting was the key designer
- Mostek developed the first address multiplexed DRAM, the 4Kbit MK4096 in 1973



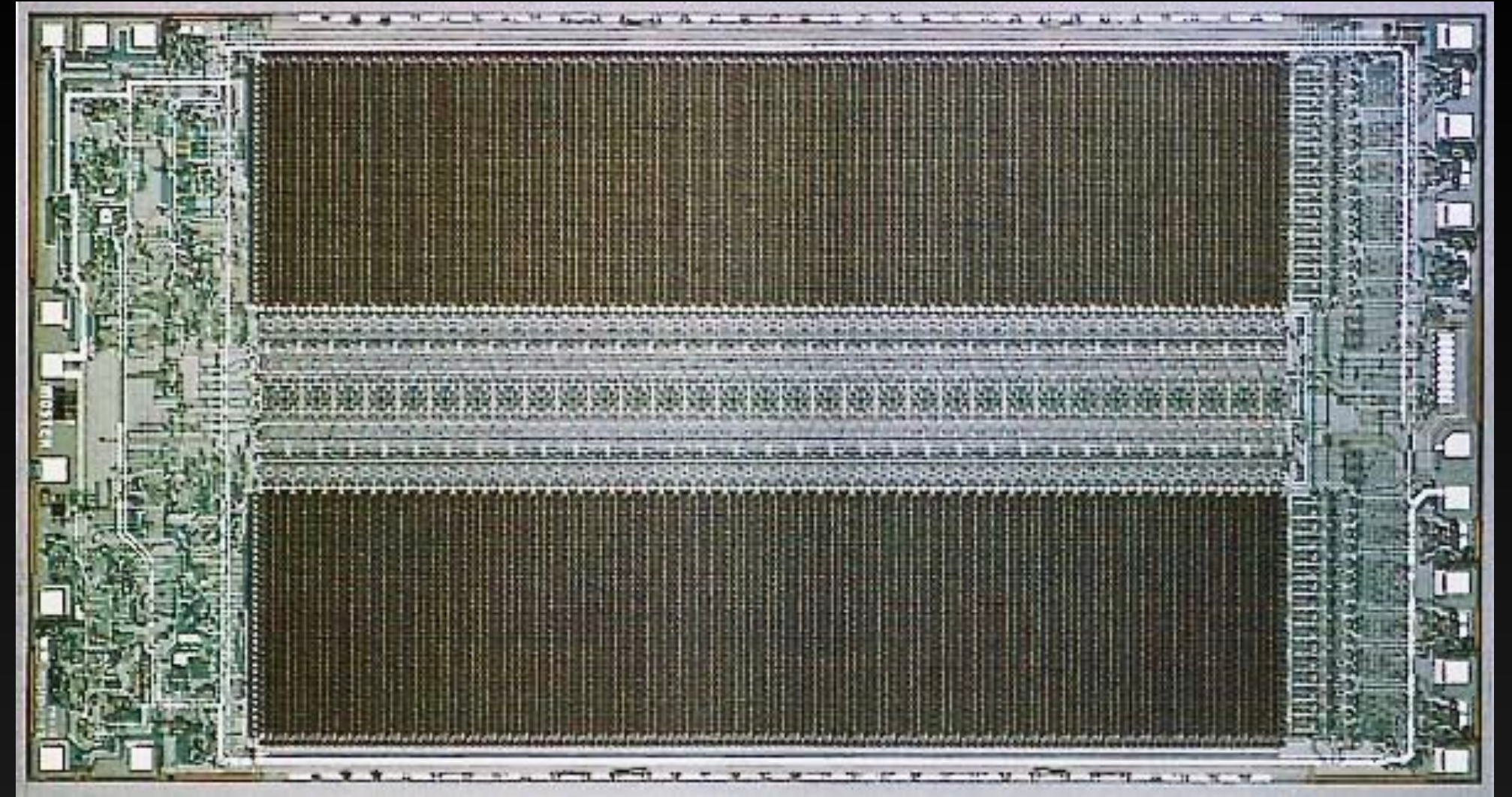
Mostek MK4096 4Kbit DRAM



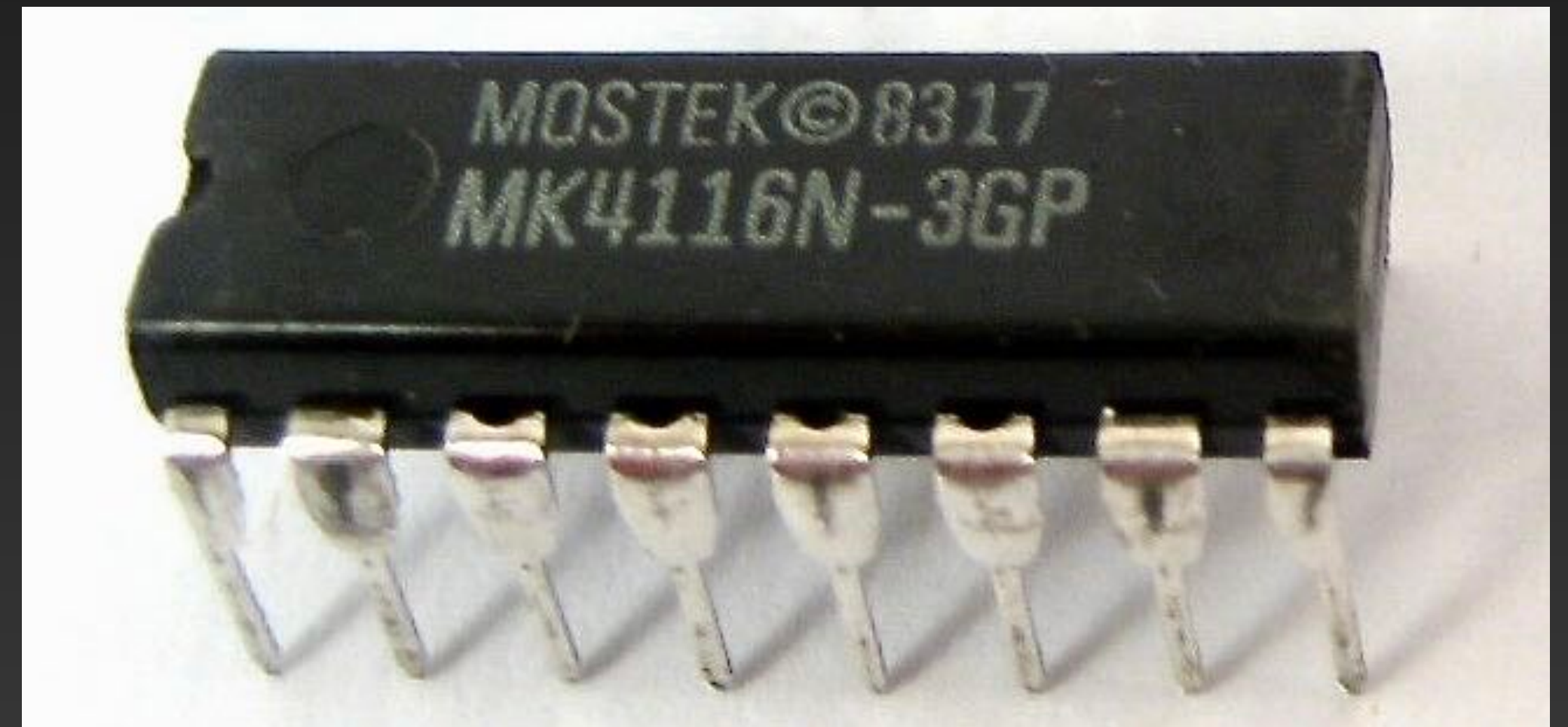
History of the DRAM

Creating The New Main Memory

- Mostek developed a address multiplexed 16Kbit DRAM, the MK4116 by 1976
- Paul Schroeder was the key designer



Mostek MK4116 16Kbit DRAM



History of the DRAM

NCR Microelectronics

First DRAMs Built on Silicon Mountain

- NCR Corporation sent a 12 man team to open a semiconductor fab in 1975 and build a DRAM
- After attempting to develop their own, NCR Microelectronics licensed MK4116 16K DRAM from Mostek
- Produced 16K DRAM through 1984
- NCR Fab later owned by AT&T, Symbios Logic, LSI Logic
- NCR Fab now owned by dpiX, a leading X-ray Sensor Company since 2011



Former NCR Microelectronics Fab
Now dpiX at 1635 Aeroplaaza Drive
Colorado Springs, CO

History of the DRAM

Creating The New Main Memory

- By 1976, Mostek held 85% market share in DRAM and was ready to expand to a new facility
- By the late 1970s, Japanese companies were entering the DRAM market. Dark clouds were gathering.
- Mostek would be late to market with their 64Kbit DRAM

Table 6.3 The changing patterns of market leadership in DRAMs

Memory introduction dates and the initial leading four firms in each market segment:

Date	1974	1976	1979	1979	1982	1985
Leading firms	Intel TI Mostek NEC	Mostek Intel NEC Fujitsu	Intel Hitachi Fujitsu Motorola	Motorola Fujitsu Hitachi TI	Hitachi Fujitsu NEC AT&T	Toshiba Hitachi AT&T NEC

Number of major suppliers in world market three years after introduction of DRAM:

Date	1974	1976	1979	1979	1982	1985
DRAM size	4K	16K*	16K	64K	256K	1Mb
Japanese	1	4	2	6	6	7
US	8	8	5	3	5	4
European	1	2	0	0	0	1
Korean	0	0	0	0	0	1

Source: Based on data from Dataquest Europe, Denham UK

Note: One of the four US producers of the 1Mb DRAM within three years of its introduction was the previously captive producer AT&T

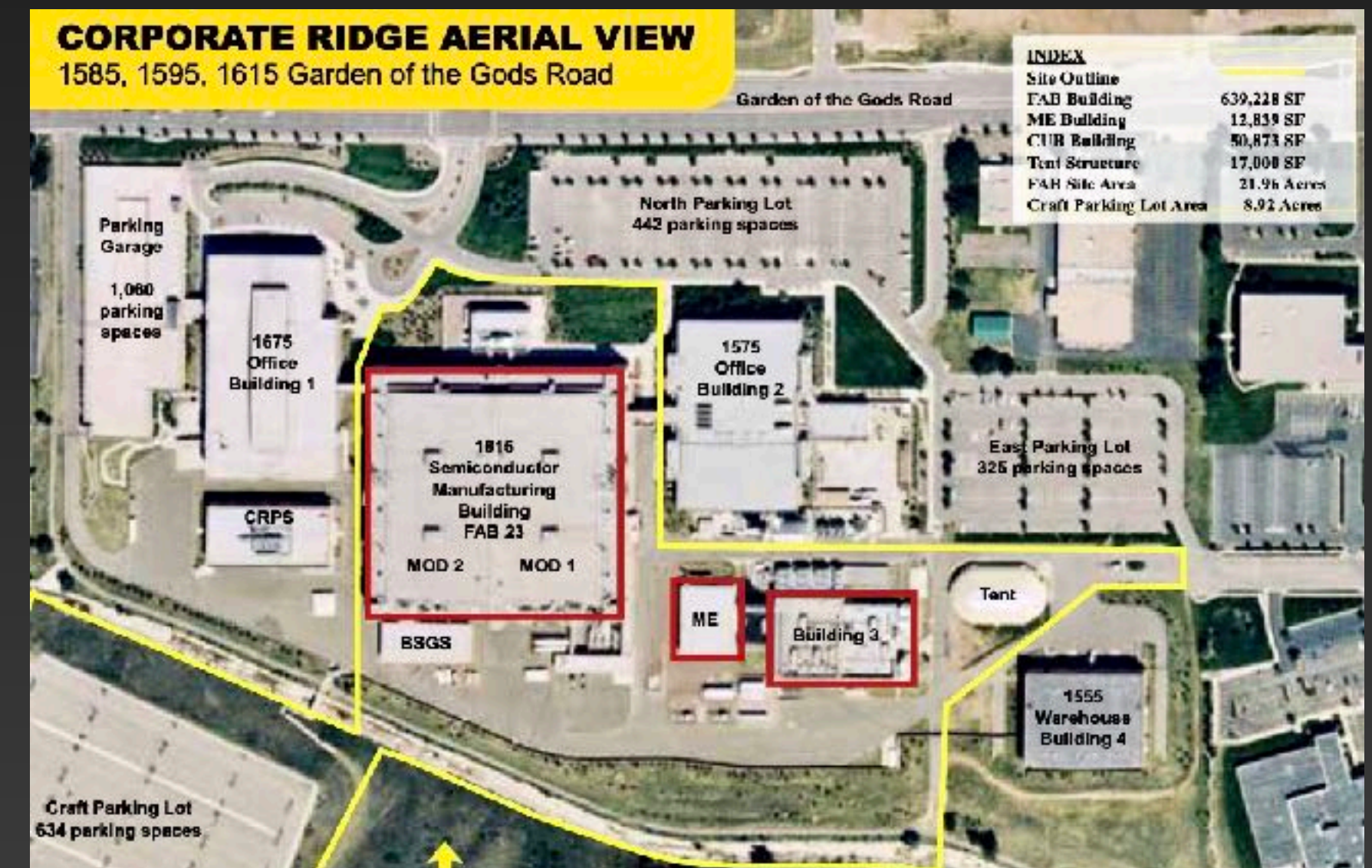
History of the DRAM

Creating The New Main Memory

- Mostek would build a major DRAM factory on Garden of Gods Road in Colorado Springs by early 1980s.
- This facility would build 64Kbit and 256Kbit DRAM
- This facility would later become UTMC, Rockwell International, and Intel Fabs



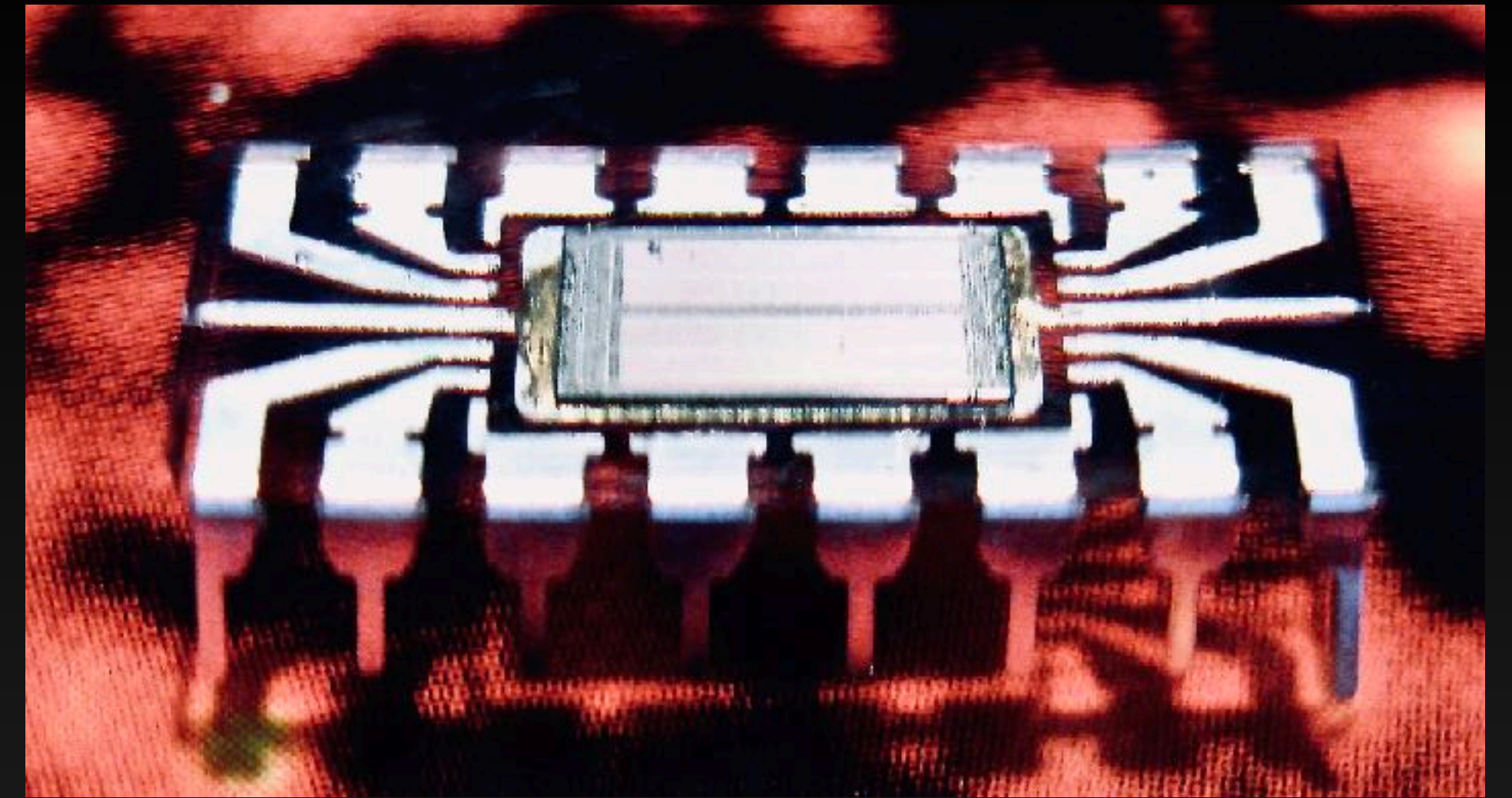
Mostek DRAM Fab would Grow Into
a Major Facility for Intel



History of the DRAM

Creating The New Main Memory

- Mostek would launch the 64Kbit MK4564 from the Colorado Springs fab
- By 1981, Fujitsu, Hitachi, Mitsubishi, NEC, and Oki had entered the 64K DRAM market
- DRAM Demand would peak in 1984
- During a market downturn in 1985, demand would decrease and increasing competition would drive Mostek to major losses
- Intel & TI would leave the DRAM Market in 1985, AT&T would leave the market in 1987
- Mostek would be sold to United Technologies. The DRAM business would be sold to SGS-ATES which would later become STMicroelectronics
- The United Technologies Microelectronic Center (UTMC) would focus of military grade memory and microprocessors occupying a part of the former Mostek Fab



Mostek MK4564 64Kbit DRAM would be the primary product of Colorado Springs Fab



History of the DRAM

Creating The New Main Memory

- 1979 - Inmos Corporation was formed with support from the British Enterprise Board
- Founders were Paul Schroeder, Ian Barron, and Dr. Richard Petritz
- The Inmos DRAM Design & Manufacturing facility was located in Colorado Springs, CO



Founders -Paul Schroeder, Ian Barron,
and Dr. Richard Petritz

History of the DRAM

Creating The New Main Memory

- US Facility was Located on Cheyenne Mountain next to the Honeywell Semiconductor Facility
- Inmos would develop SRAM, DRAM, and Transputers
- It would manufacture & sell 64Kbit DRAM built in Colorado Springs
- Sold to Thorn EMI by the British Government in 1984
- It would reach \$68 Million in Revenue by 1986
- In 1986, Inmos designed a high performance 256K DRAM for NMB Semiconductor in Tateyama, Japan
- The 256K DRAM was the world's first CMOS DRAM product and fastest with 60 ns cycle time. The rest of the DRAM industry would switch to CMOS at 1Mbit.



History of the DRAM

Ramtron, Non-Volatile DRAM

- Ramtron Australia Ltd. was founded in 1984 in Colorado Springs by George Rohrer, Dr. Carlos Araujo, and Larry McMillan
- Ross Lyndon-James would be the first CEO
- Ramtron developed Ferroelectric RAM technology emerging from the UCCS Microelectronics Laboratory



Ramtron HQ in Colorado Springs

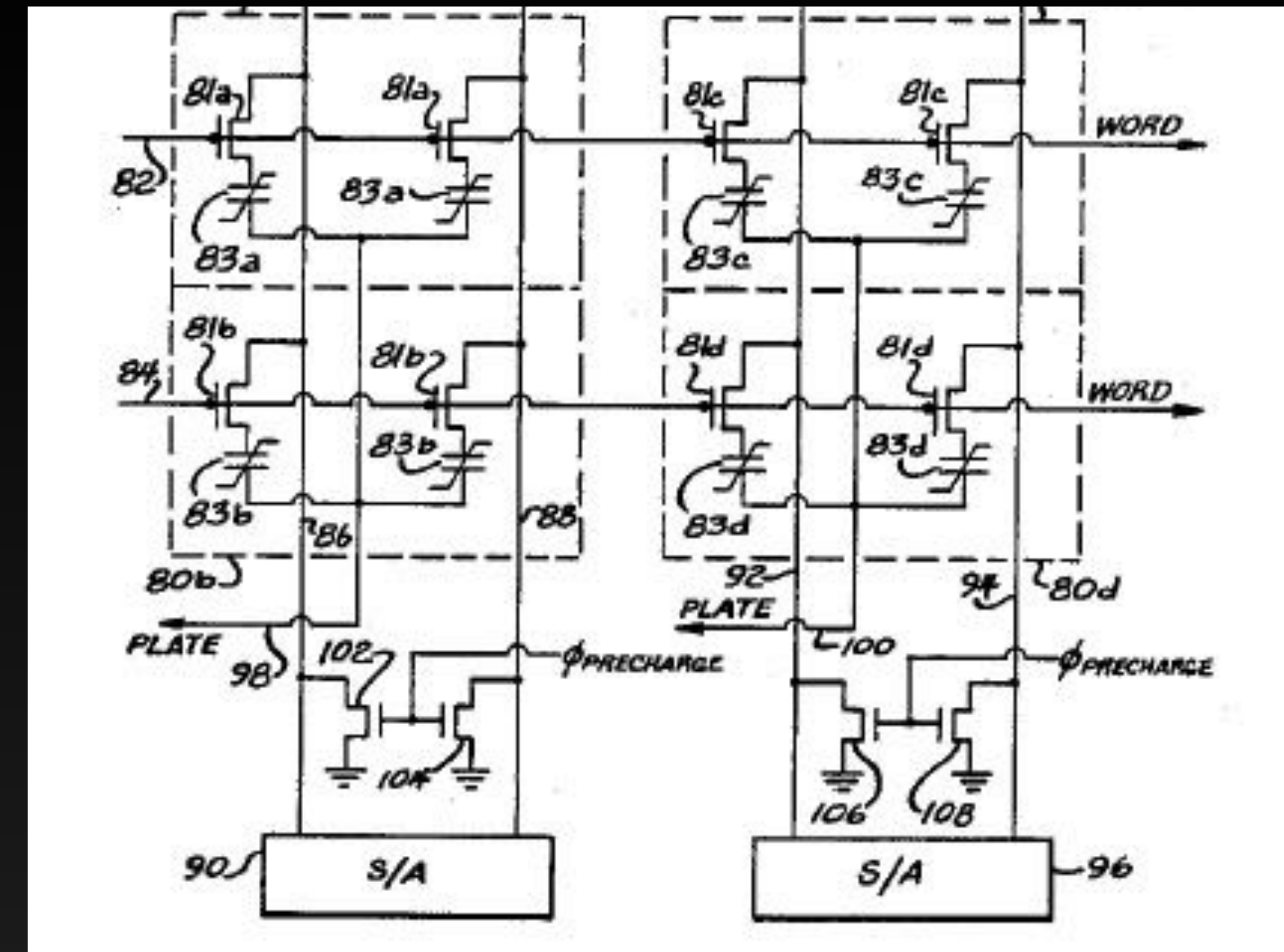


George Rohrer, Larry McMillan, Ross Lyndon-James on University of Colorado-Colorado Springs Campus

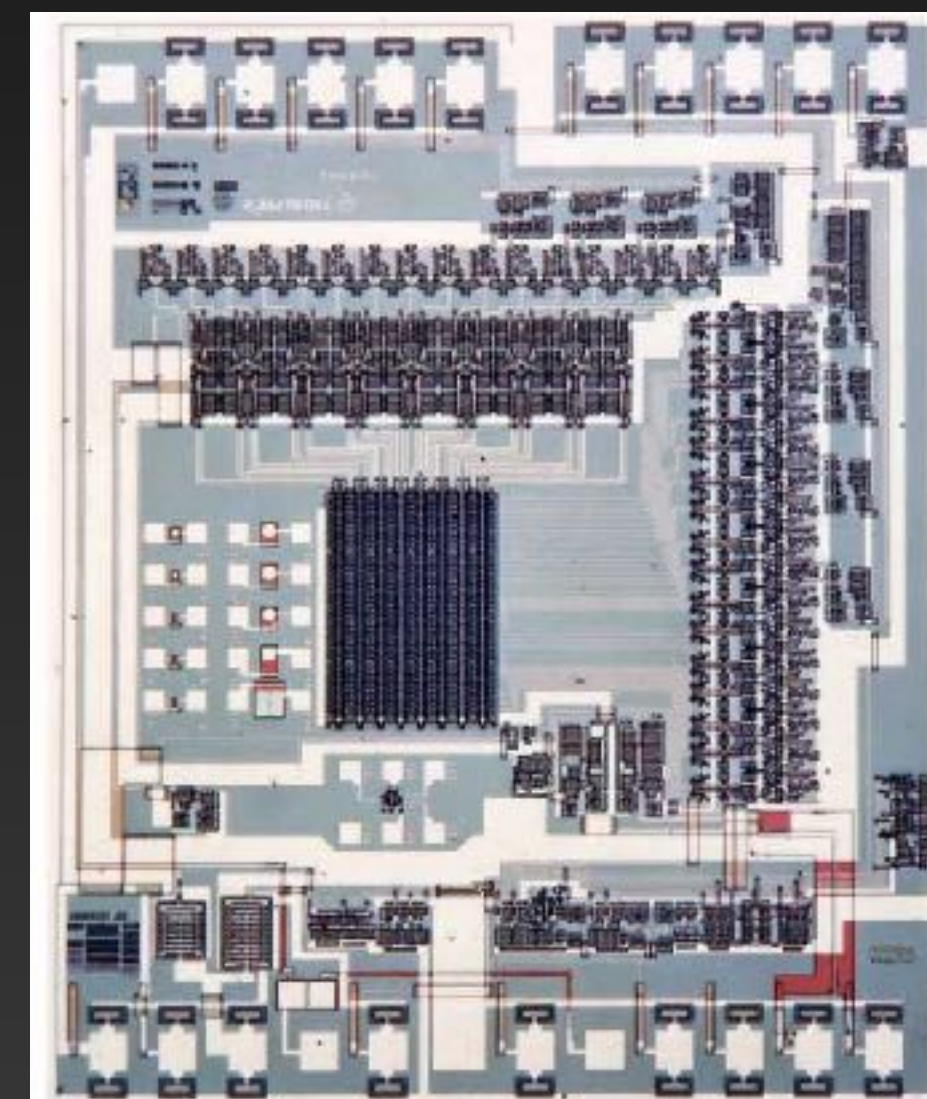
History of the DRAM

Ramtron, Non-Volatile DRAM

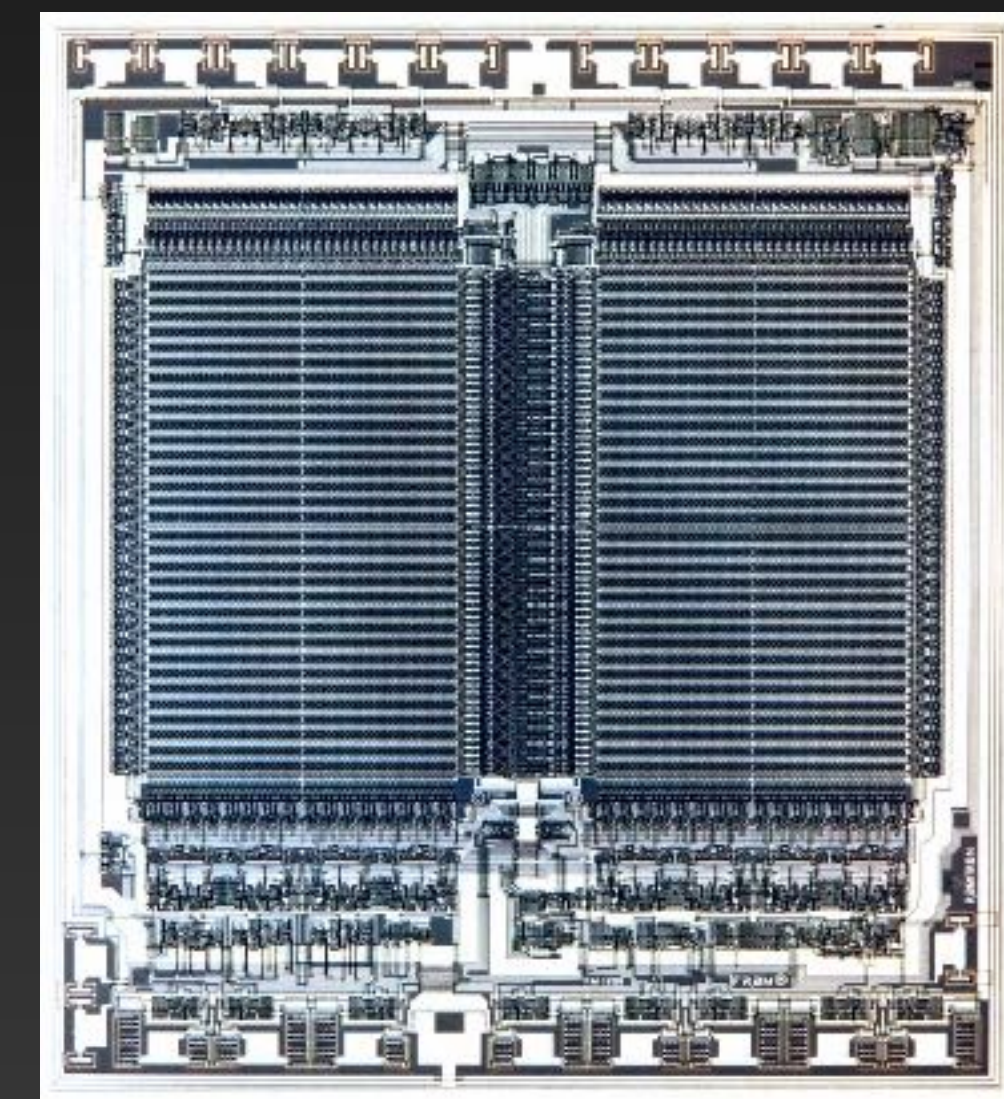
- In 1986, Ramtron hired key personnel from Inmos.
 - Dr. Fred Gnadinger as VP of R&D
 - Sheff Eaton and his team of DRAM designers to develop FRAM Memory
- Sheff Eaton patented the first 1T-1C ferroelectric RAM, a non-volatile DRAM
- By 1988, Ramtron demonstrated the first 256-bit Ferroelectric RAM
- The Inmos DRAM team developed the first production 4K FRAM in 1989.



Ramtron Patented 1T-1C FRAM Cell



FMx8101 256-bit 2T2C FRAM



FM1208 4K 2T2C FRAM

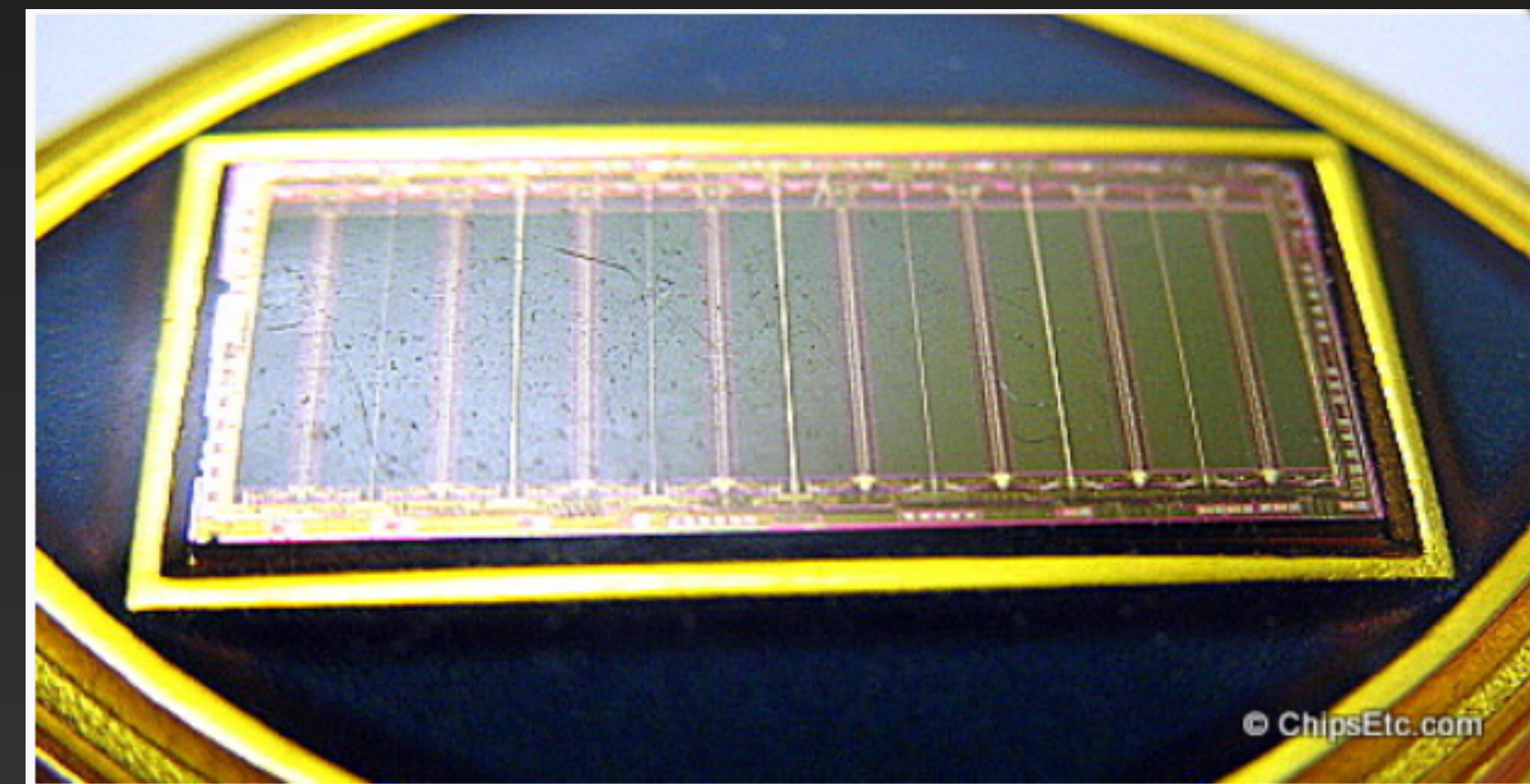
History of the DRAM

United Memories Inc.

- In 1990, Ramtron formed a joint venture company called United Memories with NMB Semiconductor (Tateyama, Japan)
- Ramtron DRAM Design Team Moved to United Memories
- NMBS Built a \$300M DRAM Fab in Japan
- United Memories designed 1Mbit & 4Mbit Fast CMOS DRAM Products for NMBS
- These DRAMs were the Fastest DRAMs Available at 60 ns Cycle Time.
- Ramtron Received Design Fees and Royalties From NMBS DRAM Sales



**Bob Gower, CEO of United Memories
Sheff Eaton becomes President**



**Ramtron-NMBS 4Mbit DRAM (60 ns)
World's Fastest DRAM**

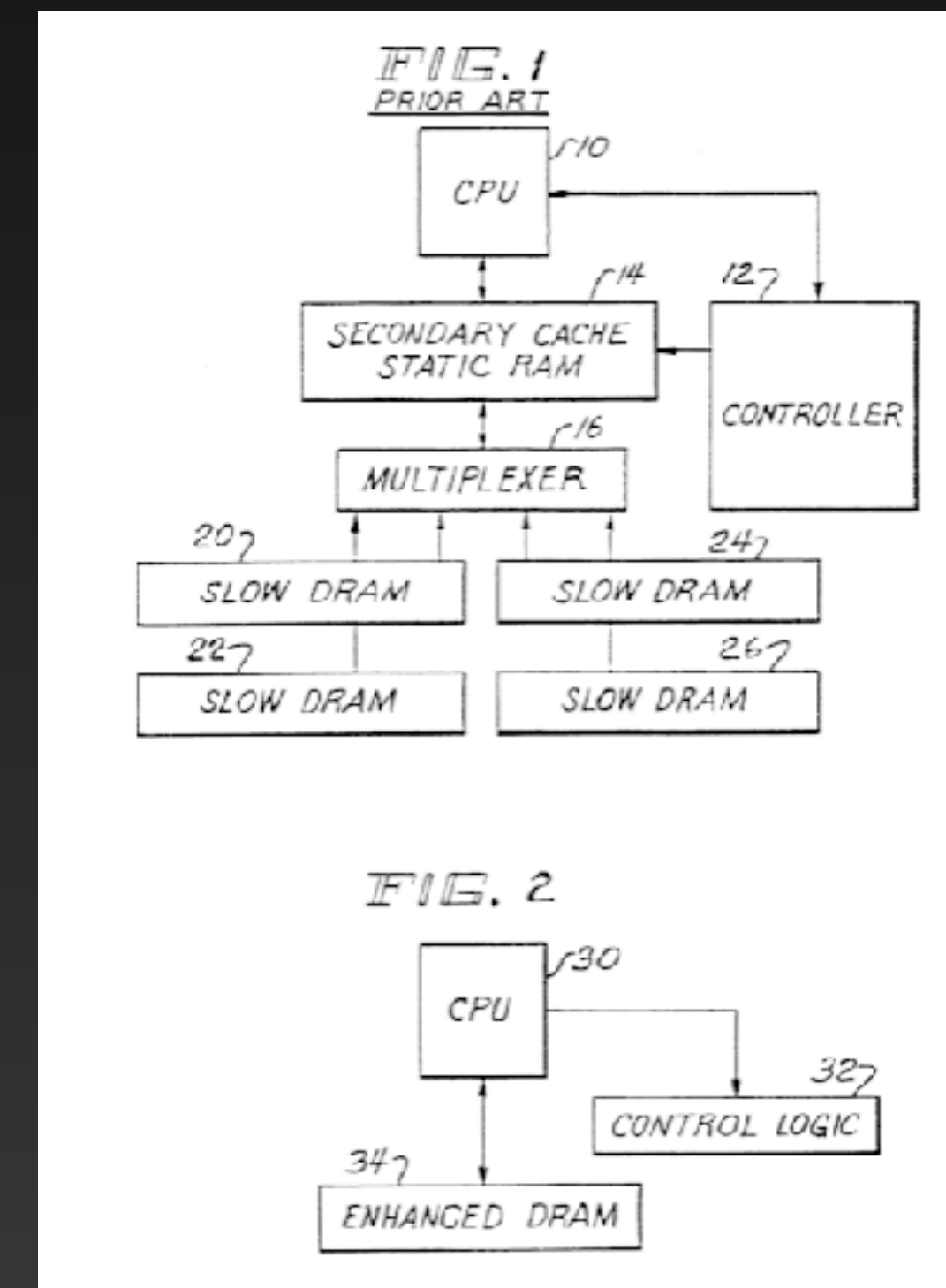
History of the DRAM

Ramtron Enhanced DRAM (EDRAM)

- In 1990, Ramtron decided to develop a unique DRAM product based on NMBS fast DRAM technology
- Cheetah International in Colorado Springs was building fast PCs based on available DRAMs
- Ramtron, United Memories, and Cheetah International defined the Enhanced DRAM, a Cached DRAM
- EDRAM Targeted the Emerging High-end PC Market
- United Memories modified NMBS 4Mbit DRAM with integrated SRAM cache row registers
- NMBS prototyped the 4Mb EDRAM by 1991
- The EDRAM Became the Fastest 4Mbit DRAM Product on the market by 1992



Ron Sartore, President of Cheetah International



Patent #6,347,357

Enhanced DRAM with
Embedded Registers

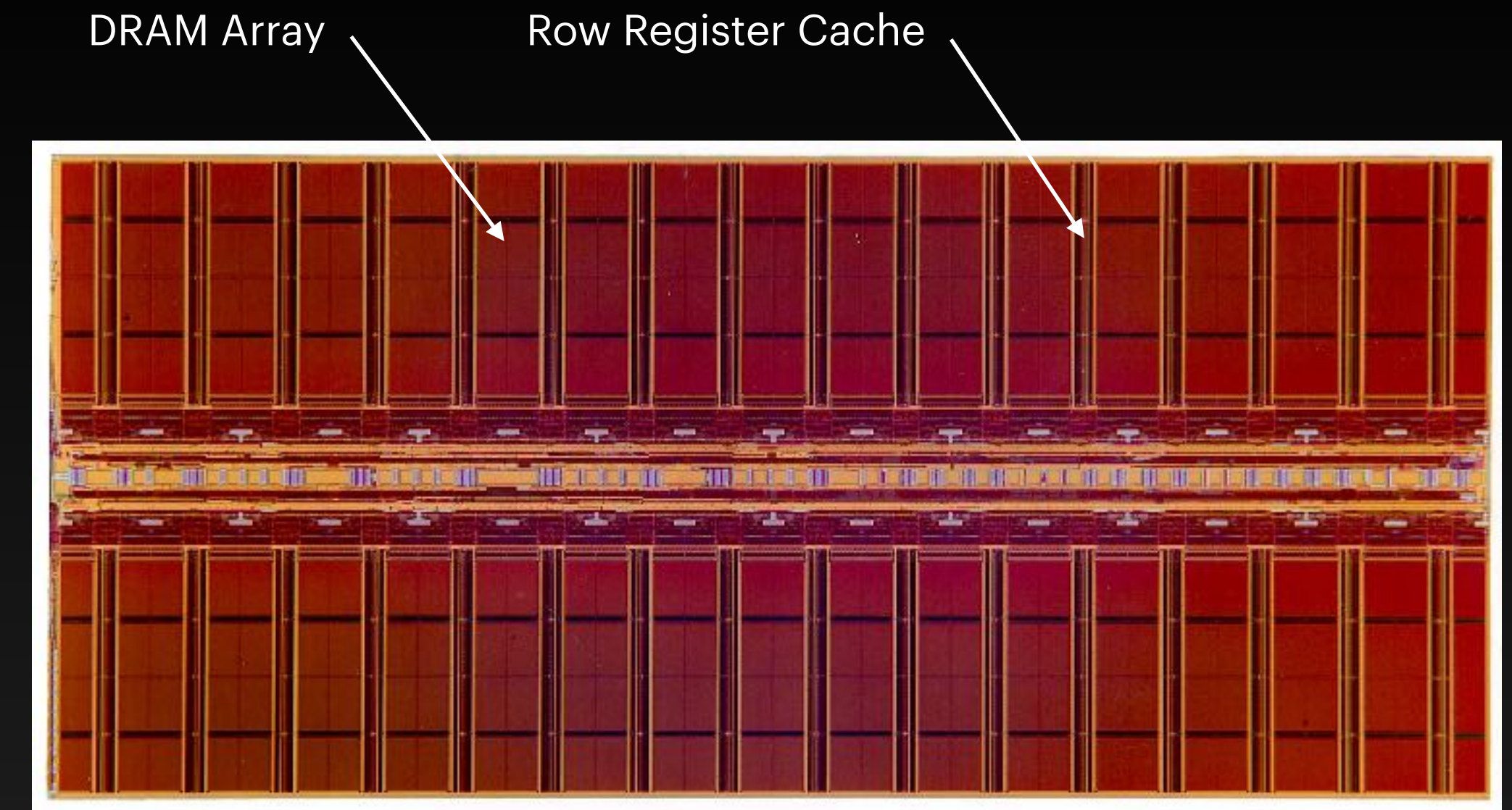
Sartore, Mobley, Carrigan, and
Jones

1/22/92

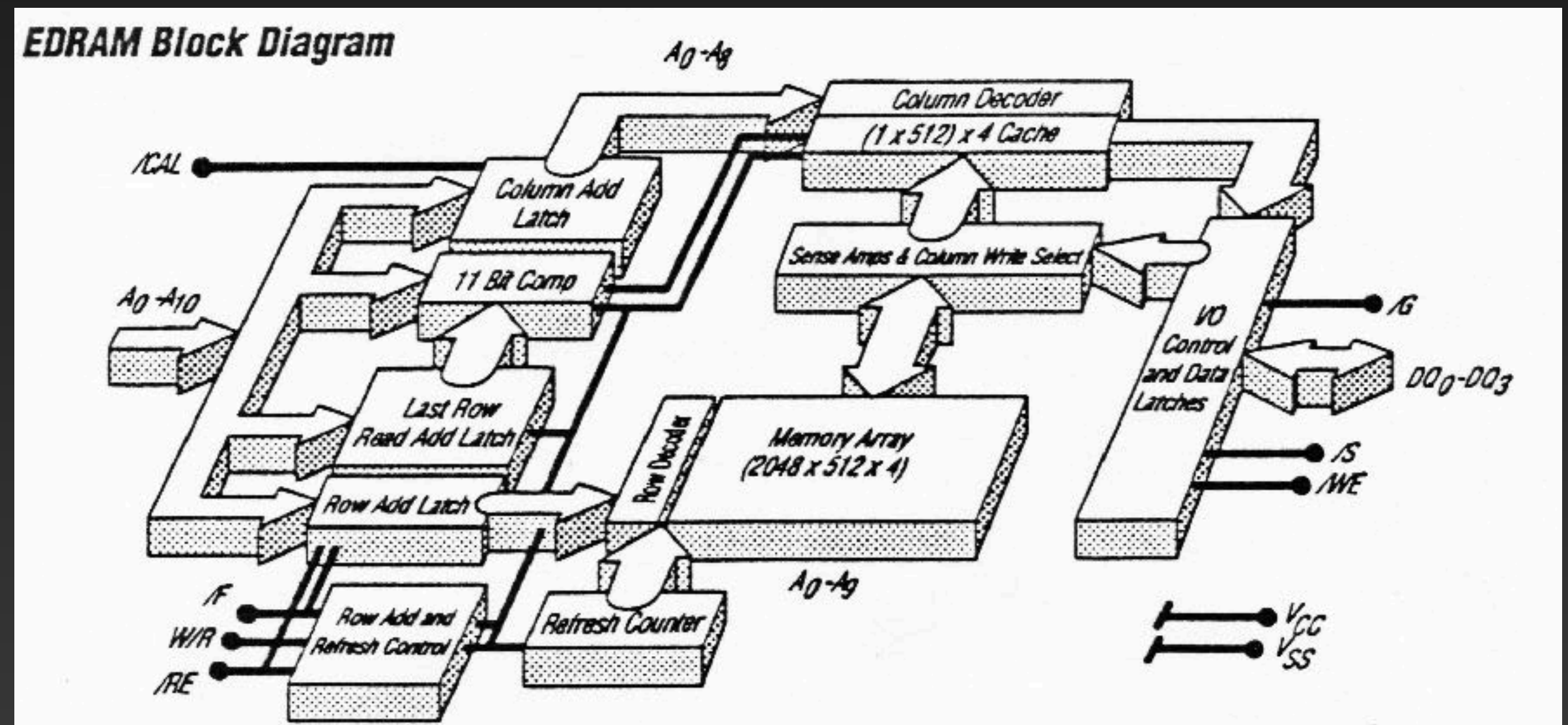
History of the DRAM

Ramtron Enhanced DRAM (EDRAM)

- Ramtron Enhanced DRAM (EDRAM) integrated a 2Kbit SRAM Row Cache into the NMBS Fast DRAM Core
- While Pin Compatible with Standard 4Mbit Asynchronous DRAM, EDRAM could randomly read or write data within a row in 15ns
- If an access to EDRAM missed the cached Row, read access time was 35 ns
- Unlike Standard DRAM, EDRAM could be refreshed at the same time data was read or written to the Row Cache
- This architecture would allow data read & write operations with zero wait states like SRAM cache
- EDRAM was introduced in January 1992, was sampled in July 1992, and entered production in January 1993
- EDRAM would be produced for over 8-years



Enhanced DRAM Die



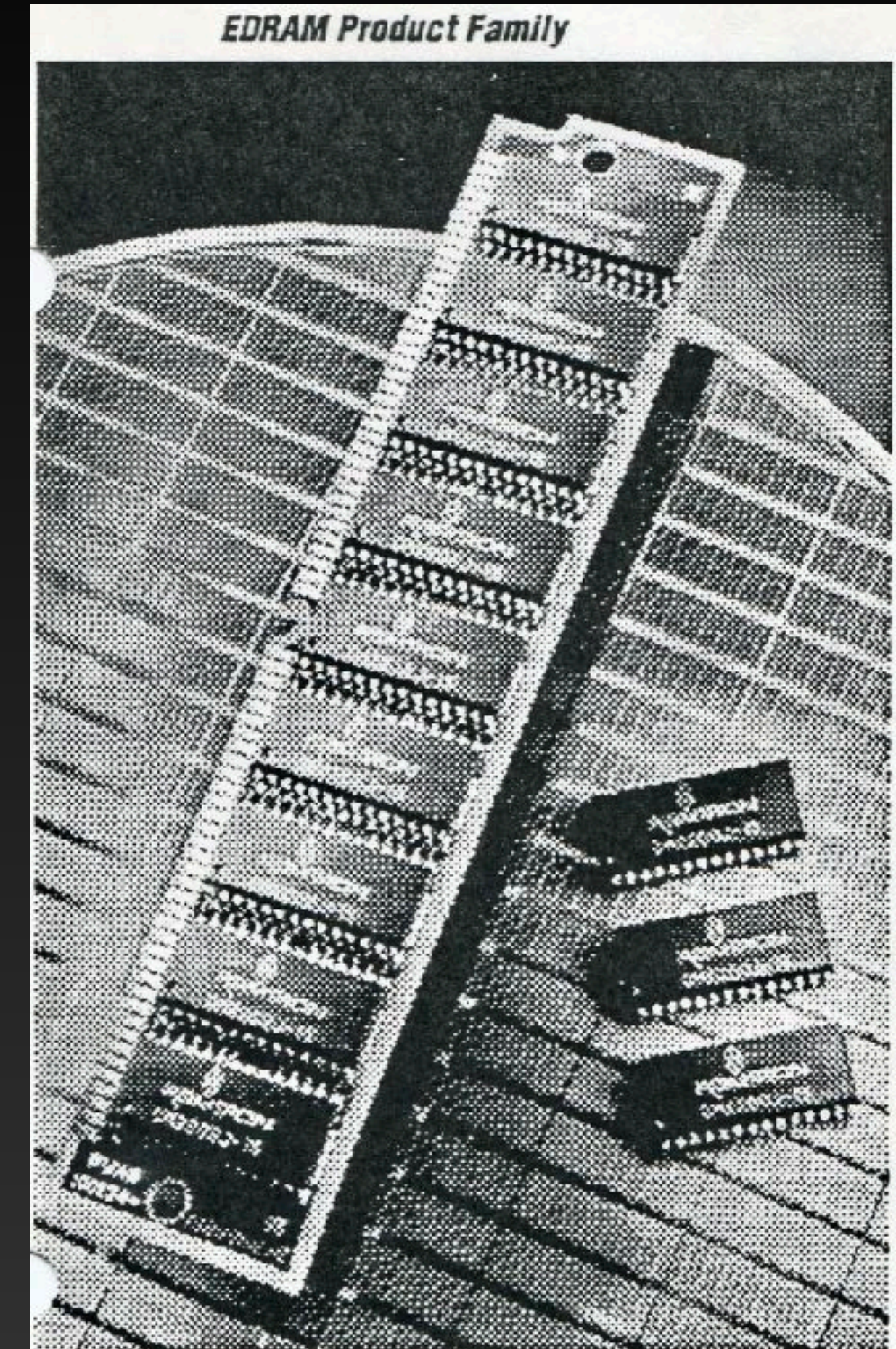
History of the DRAM

Ramtron Enhanced DRAM (EDRAM)

DRAM Performance Comparison

<i>Mode</i>	<i>15ns EDRAM</i>	<i>70ns DRAM</i>	<i>Comment</i>
Random Cycle Time	65ns	130ns	2X Faster
Random Access Time	35ns	70ns	2X Faster
Page Read Cycle Time	15ns	40ns	2.7X Faster
Page Access Time	15ns	35ns	2.3X Faster
Page Miss Access Time	35ns	130ns	3.7X Faster
First Write-In Page	15ns	40ns	2.7X Faster
Page Write Cycle Time	15ns	40ns	2.7X Faster

EDRAM was more than 2X Faster Standard DRAM

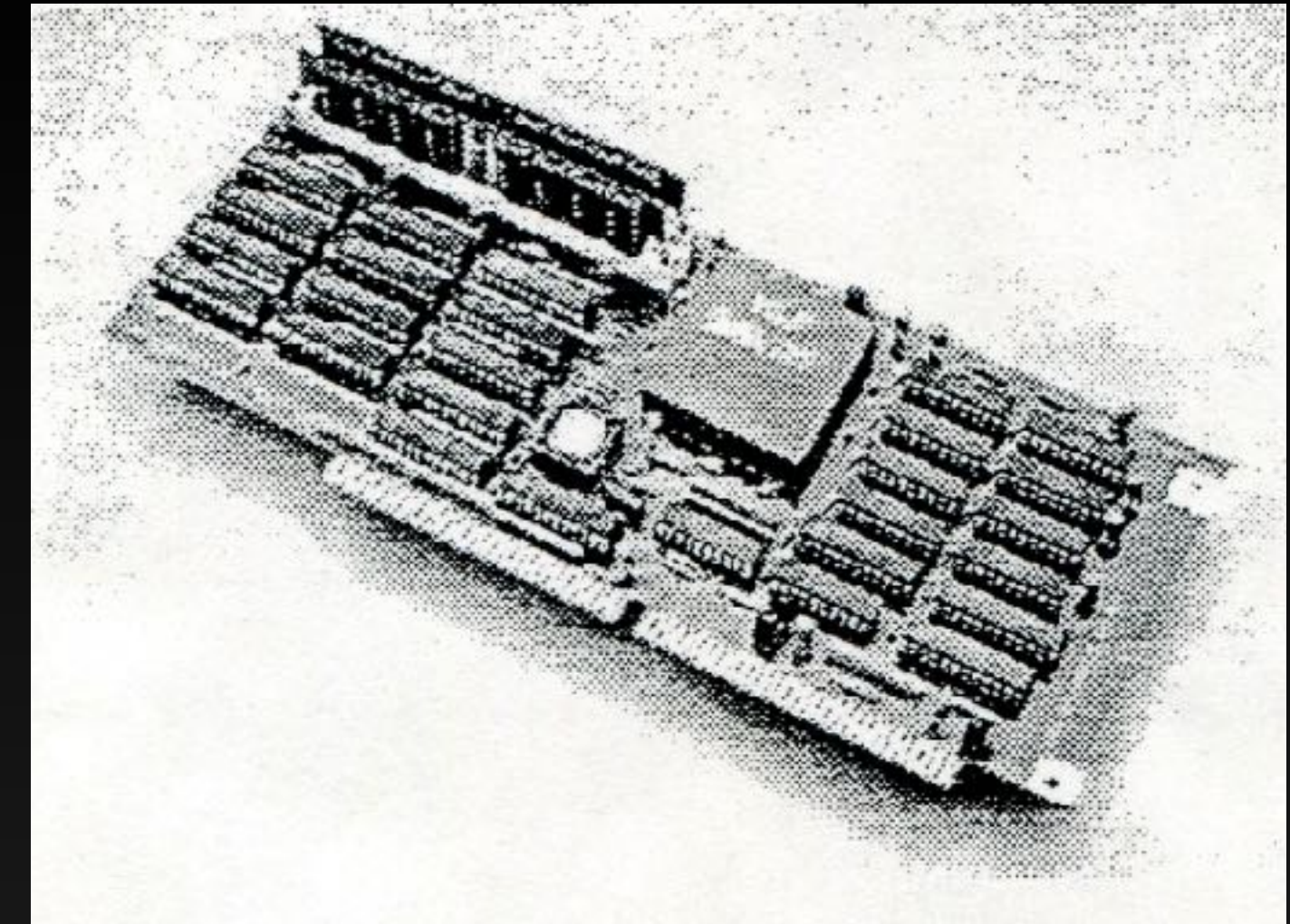


Original Product Picture 1992

History of the DRAM

The World's Fastest PCs

- EDRAM was first disclosed publicly at the First Silicon Valley PC Conference in 1991
 - Ron Sartore documented his modified Cheetah Gold 486-33 System with EDRAM
 - “New Generation of Fast, Enhanced DRAMs Replace SRAM Cache in High-End PC Workstations”
 - He found EDRAM faster than several Fast Memory Alternatives
- Ramtron Approached Intel For Support In Developing an Intel Motherboard
 - Ed Solari of Intel Hillsboro provided an existing Intel Motherboard Design and Recommended Dr. Design, an Intel Contractor to support the Ramtron Design
 - First Ramtron PC Design was disclosed at the Third Silicon Valley PC Conference in 1993
 - “Cacheless Fast DRAM Memory System Improves 486DX2-66 System Performance”
 - System Demonstrated Clear Advantage over SRAM Cache in Unix Benchmarks and Basic Memory Tests



Ramtron 486DX2-66 with EDRAM

PC Labs V7.0			
Processor			
EDRAM	16626.36		EDRAM ADVANTAGE
256K Cache	16394.00	1.4%	
DRAM	10244.00	62.3%	
Memory			
EDRAM	9440.00		EDRAM ADVANTAGE
256K Cache	5599.00	68.6%	
DRAM	6905.00	36.7%	
Byte DOS V2.2 CPU Index			
EDRAM	2.13		EDRAM ADVANTAGE
256K Cache	1.63	26.0%	
DRAM	1.33	60.2%	
Norton SI V6.01 CPU Index			
EDRAM	90.00		EDRAM ADVANTAGE
256K Cache	90.90	-0.5%	
DRAM	66.90	35.3%	

Winbench V1.2			
EDRAM	17.53		EDRAM ADVANTAGE
256K Cache	17.52	-0.5%	
DRAM	13.89	25.2%	
SPECINT92 (50MHz)			
EDRAM	21.90		EDRAM ADVANTAGE
256K Cache	20.50	6.8%	
DRAM	16.50	32.7%	
SPECFP92 (50MHz)			
EDRAM	13.70		EDRAM ADVANTAGE
256K Cache	11.50	19.1%	
DRAM	10.40	31.7%	

Benchmark Results

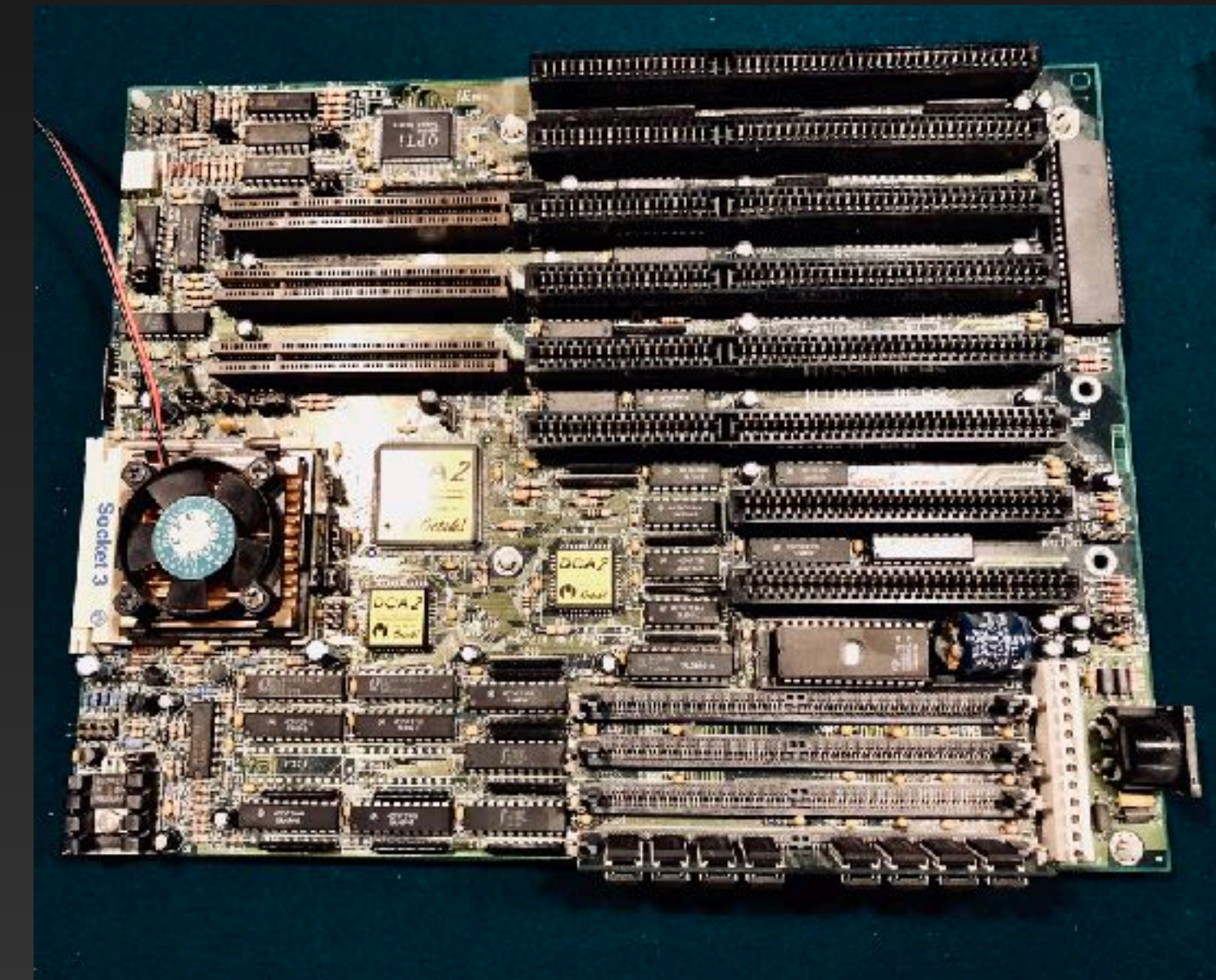
History of the DRAM

The World's Fastest PCs

- Based Upon It's Work with Intel, Ramtron Developed a Custom Chipset Based Upon Intel FlexLogic FPGA
 - Won First Taiwan Motherboard Design with Digicom
 - It was first demonstrated at Comdex 1993
 - By July 1994, Softwin Reports tested Digicom System vs. Dell OptiPlex with 128KB SRAM cache vs. 66MHz Pentium with 512KB SRAM Cache
 - Softwin Found Digicom 486DX2-66 approached Pentium System performance
- Ramtron worked with Ocean Information Systems (Hong Kong) who developed their own optimized chipset in 1994
 - Softwin Reports awarded Ocean DCA2 their Top Gun Award as the fastest 486DX4-100 System tested and faster than a Pentium 100MHz system



Digicom 486DX2-66 Motherboard with EDRAM



Ocean Information Systems 486DX4-100
DCA2 Motherboard With EDRAM

History of the DRAM

Enhanced Memory Systems

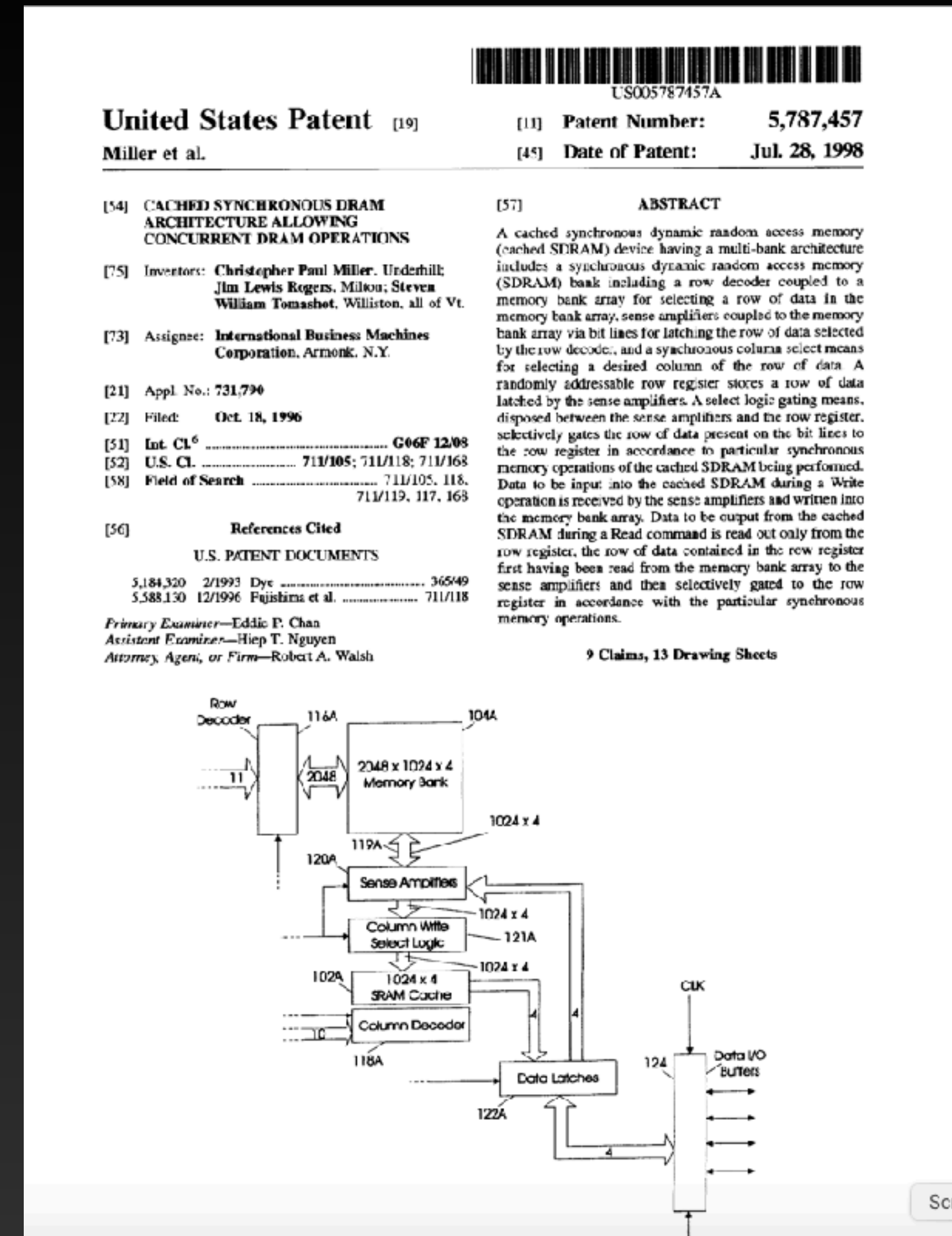
- In 1995, Ocean would be ready to place \$100M order for EDRAM
- Ramtron's Major Investor, Oren Benton was going Bankrupt
- Ramtron could not fund the work in process (WIP) to take the order
- Based upon test results from EDRAM Motherboards, Ramtron would negotiate a second sourcing agreement with IBM
- Ramtron would spin-out EDRAM Business as separate subsidiary, Enhanced Memory Systems
- Enhanced Memory Systems would refocus business on SRAM Replacement and reach \$16M Revenue in 1986



Enhanced Memory Systems Product Picture 1995

History of the DRAM Enhanced Memory ESDRAM

- Enhanced Memory would produce 4Mb EDRAM at IBM's Factory in Essonnes, France
- Enhanced Memory and IBM would invent and patent the Enhanced Synchronous DRAM (ESDRAM)
- A 16Mb ESDRAM product family would be built at IBM but would be late to market and not a factor in the PC main memory market
- PC focus would shift to Licensing EDRAM Technology to Mainstream DRAM Manufacturers
- In 1998, ESDRAM and DDR ESDRAM would become JEDEC Superset DRAM Standards



ESDRAM Patent #5,787,457 Later Assigned to Bondurant, Jones, and Moble

History of the DRAM

Enhanced Memory HSDRAM

- Enhanced Memory would negotiate a foundry agreement with Infineon (Dresden, Germany) and design a 64Mbit ESDRAM but it would not make it to the market
- To recapture the high performance PC Market, Enhanced Memory would procure a high speed version of a conventional DRAM with PowerChip Semiconductor (Taiwan)
- The Enhanced HSDRAM would achieve 2:2:2 latency at 133 MHz and could be overclocked to up to 166 MHz

Operating Frequency	CAS Latency	64MB DIMMs Installed	128MB DIMMs Installed
150	3	2	2
143	3	2	2
138	3	3	2
133	3	4	3
133	2	2	2
125	2	3	2
112	2	4	4
100	2	4	4

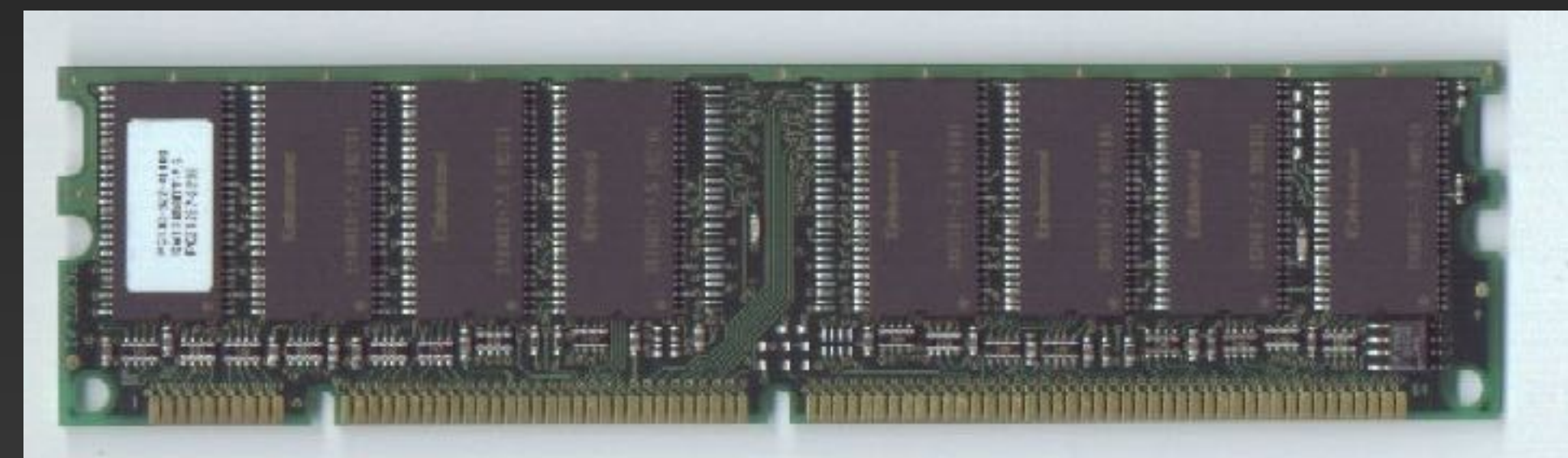
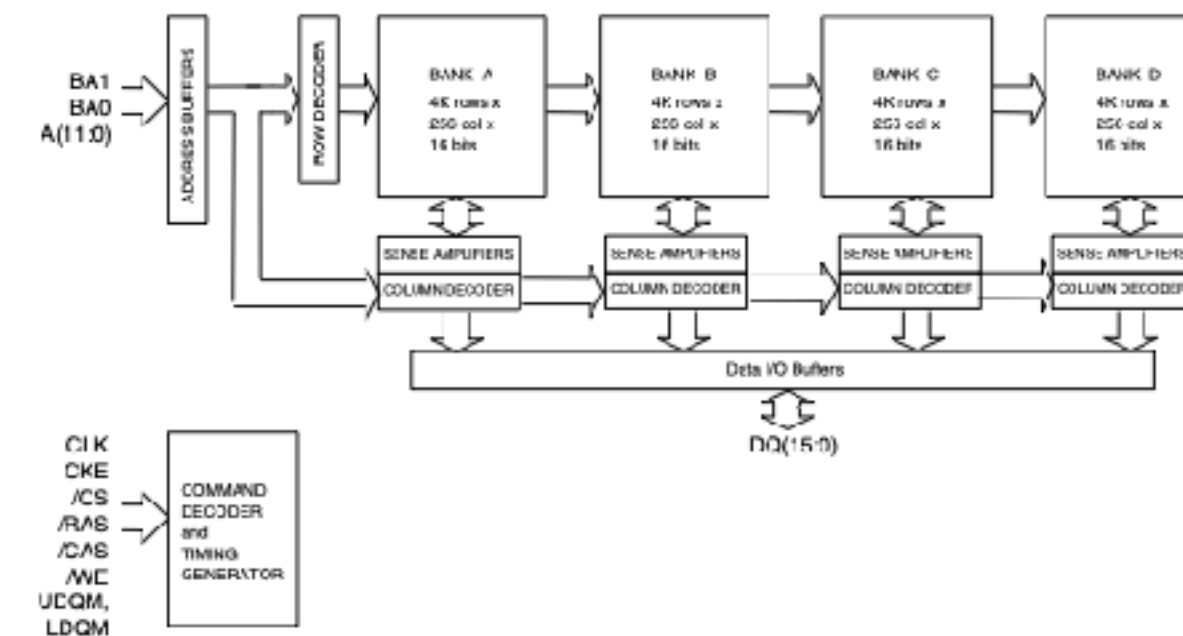
Features

- JEDEC Standard PC-133 SDRAM
- Fast 4.5 ns Clock Access Time
- Low Latency Operation (3:2:2 @ 150 MHz)
 - CAS Latency = 3
 - RAS to CAS Delay = 2
 - Precharge Delay = 2
- Fast Random Access Time (31.2 ns)
- Fast Random Cycle time (53.3 ns)
- Programmable Burst length (1, 2, 4, 8, full page)
- Programmable CAS Latency (2, 3)
- Low Power suspend, Self Refresh, and Power Down Modes Supported
- 4K Refresh / 64 ms
- Single 3.2V ± 0.3V Power Supply
- 54-pin TSOP-II (0.8mm pin pitch)

Description

The Enhanced Memory Systems SM3603 and SM3604 High-Speed SDRAM (HSDRAM) devices are high performance versions of the proposed JEDEC PC-133 SDRAM. While compatible with standard SDRAM, they provide the faster clock access time (4.5 ns), shorter random access latency (31.2 ns), and fast bank cycle time (53.3 ns) needed to improve system stability, capacity, and performance in systems operating at 150 MHz bus speed. The HSDRAM is ideal for any high performance system including PCs, workstations, servers, communications switches, DSP systems, 3-D graphics, and embedded computers.

Block Diagram (4Mx16 shown)



Enhanced Memory Systems HSDRAM Product Picture 1999

History of the DRAM

Mushkin Enhanced Memory

- Enhanced Memory Systems would work with Mushkin, a Denver-based memory module supplier to gaming & overclocker PC markets to build HSDRAM module products
- Ramtron would buy Mushkin and make it a wholly-owned subsidiary
- The Mushkin Enhanced PC150 HSDRAM Module would achieve 2:2:2 latency at 133 MHz and could be overclocked to up to 166 MHz
- Mushkin would develop a unique DRAM heatsink design to allow stable operation at high clock rates
- Mushkin continues as a leading e-commerce supplier of memory modules, SSD modules, and other electronic components today



Mushkin Enhanced PC150 HSDRAM Product Picture 1999

History of the DRAM

Mushkin at E3, The World's Fastest Athlon 700

- Mushkin would exhibit at Electronic Entertainment Expo in Los Angeles in May 2000
- Mushkin and Enhanced Memory would develop "Freak Machine", the world's fastest Athlon 700 PC overclocked to 964 MHz



HSDRAM delivered in unique bubble pack



What is it about this memory that makes it so good? Could it be the fact that it's running at a low-latency 150 MHz, compared to 100 or 133 MHz that other memory DIMMs are known for? Maybe it's the lightning fast 4.5 ns clock access time that makes it so great. Whatever it is, you can rest assured that this is some of the best memory I have ever used, and will definitely go back to them should I wish to upgrade.

Mushkin was on display at E3 last May, where they displayed what they called their "Freak Machine." With this new memory, the Freak was running an Athlon-based PC at a previously unheard of 964 MHz. Benchmarks of Quake 3, Unreal Tournament, and Incoming all had frame rates in the triple digits! Now I know my Athlon 700 will not come anywhere near these levels, but I have noticed a considerable speed boost in my games. Unreal Tournament now runs near constant at 60 at 1024x768 resolution, and Quake 3 does the same at 800x600.

A strip of 128 MB PC150 memory runs for \$119 (as of writing this review), and it's definitely worth it. They can be found at www.mushkin.com.

Mushkin Freak Machine Shown at E3, May 2000
The Fastest Athlon 700 Overclocked to 964 MHz

History of the DRAM

The World's Highest Density SRAMs

- By 1998, Enhanced Memory Systems recognized they could not keep pace with commodity DRAM density
- Focus changed to creating 1 Transistor SRAM Products that were 4X higher density than SRAM
- Enhanced Memory negotiated a foundry agreement with Infineon (Dresden, Germany) - Infineon would take 30% Ownership Position in Ramtron/Enhanced Memory
- Enhanced Memory patented an Enhanced SRAM (ESRAM) version of ZBT SRAM
- Enhanced Memory partnered with Cypress Semiconductor (the Largest SRAM Supplier) to develop a 72-Mbit ZBT ESRAM
- Enhanced Memory Systems partnered with Hewlett Packard to develop a 72-Mbit DDR ESRAM for L3 Cache Application

United States Patent [19]
Bondurant et al.



US006151236A

[11] Patent Number: 6,151,236
[45] Date of Patent: Nov. 21, 2000

[54] ENHANCED BUS TURNAROUND INTEGRATED CIRCUIT DYNAMIC RANDOM ACCESS MEMORY DEVICE

[75] Inventors: David Bondurant; David Fisch, both of Colorado Springs; Bruce Grieshaber, Colorado Spring; Kenneth Mobley; Michael Peters, both of Colorado Springs, all of Colo.

[73] Assignee: Enhanced Memory Systems, Inc., Colorado Springs, Colo.

[21] Appl. No.: 09/515,007

[22] Filed: Feb. 29, 2000

[51] Int. Cl.⁷ G11C 15/00

[52] U.S. Cl. 365/49; 365/203; 365/222

[58] Field of Search 365/49, 203, 222

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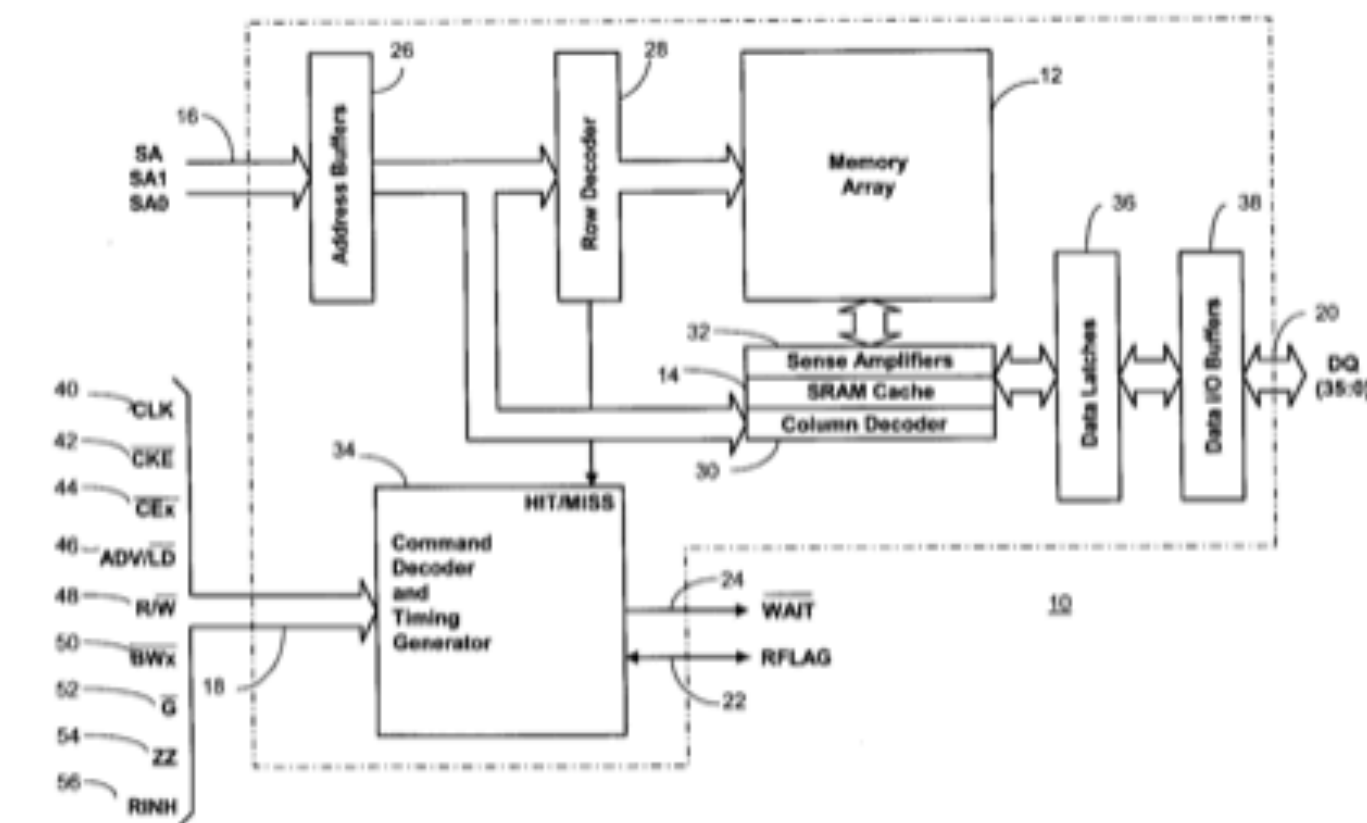
"ZBT SRAM—Frequently Asked Questions about ZBT SRAMS", Micron Semiconductor Products, Inc., Nampa, ID, Oct. 15, 1999.

Primary Examiner—Son T. Dinh
Attorney, Agent, or Firm—William J. Kubida, Esq.; Carol W. Burton, Esq.; Hogan & Hartson LLP

[57] ABSTRACT

An enhanced bus turnaround integrated circuit dynamic random access memory ("DRAM") device of particular utility in providing maximum DRAM performance while concomitantly affording a device with may be readily integrated into systems designed to use zero bus turnaround ("ZBT"), or pipeline burst static random access memory ("SRAM") devices. The enhanced bus turnaround DRAM device of the present invention provides much of the same benefits of a conventional ZBT SRAM device with a similar pin-out, timing and function set while also providing improvements in device density, power consumption and cost approaching that of straight DRAM memory. Through the provision of a "Wait" pin, the enhanced bus turnaround device of the present invention can signal the system memory controller when additional wait states must be added yet still provide virtually identical data access time performance to that of ZBT SRAM for all Read and Write operations with a burst length of four or greater. Use of master/slave and inhibit pins.

7 Claims, 8 Drawing Sheets



Enhanced Memory ZBT ESRAM Patent - 2000



One Transistor ESRAM Products

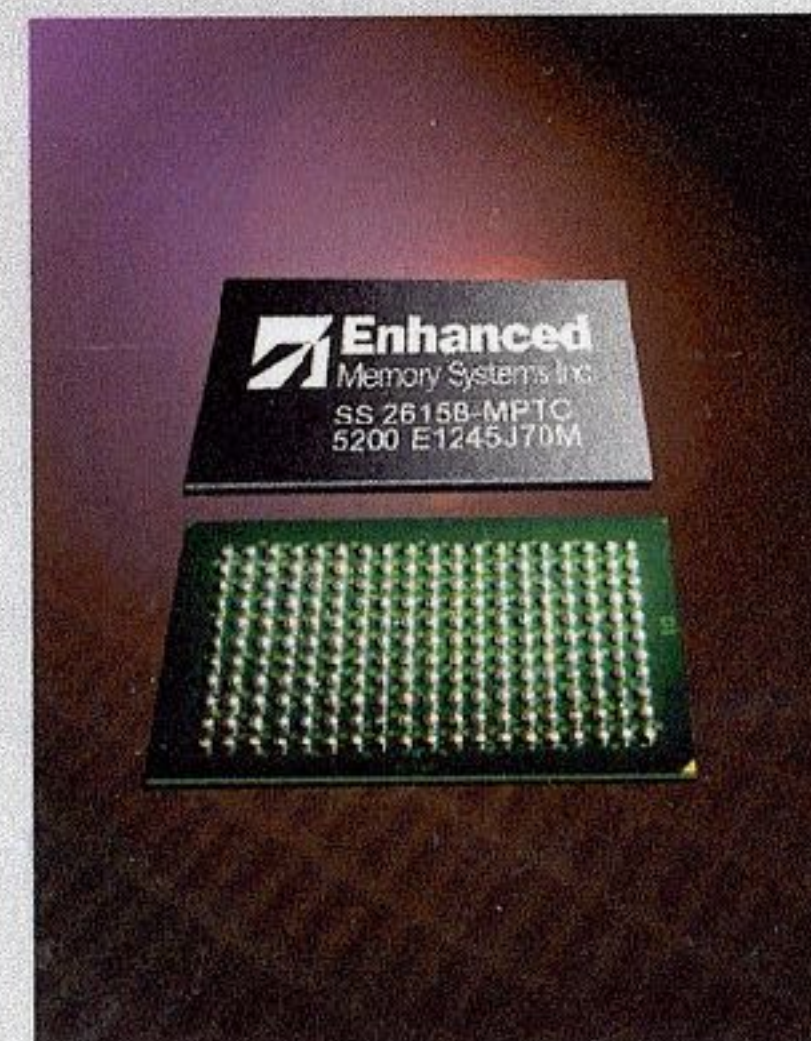
NoBL Burst SRAM

- 2Mx36
- 100, 133, 166 MHz Clock Rates
- NoBL Pin Compatible
- 100-Pin TQFP, 119-Pin PBGA
- +3.3 & 2.5 Volt I/O and Power Supply



DDR SRAM

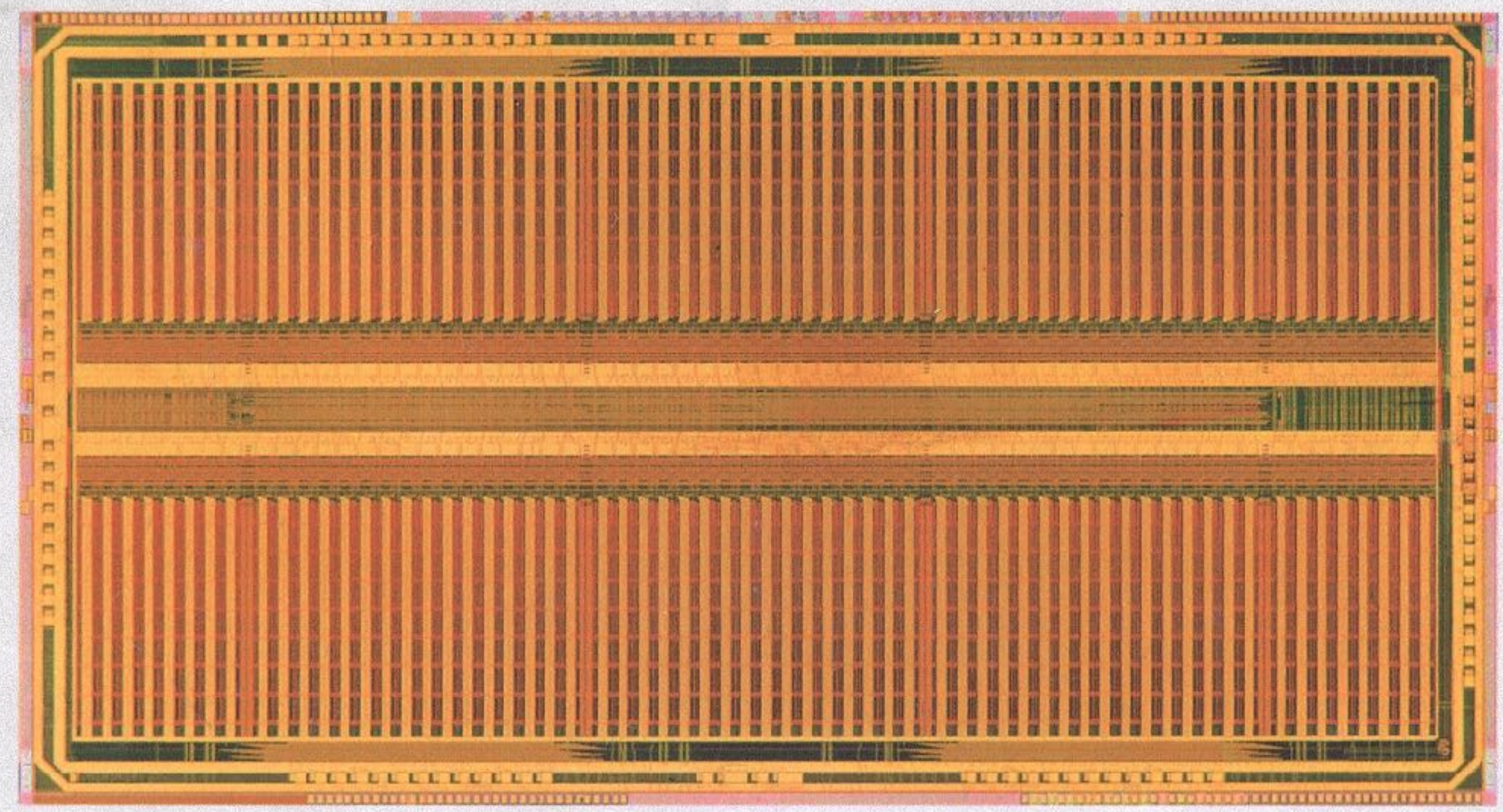
- 2Mx36
- 300 MHz Clock Rates
- 2.4GB/Second Bandwidth
- 209-Pin PBGA
- +2.5 Volt Power Supply
- +1.2 Volt HSTL I/O



RAMTRON



Die Microphotograph



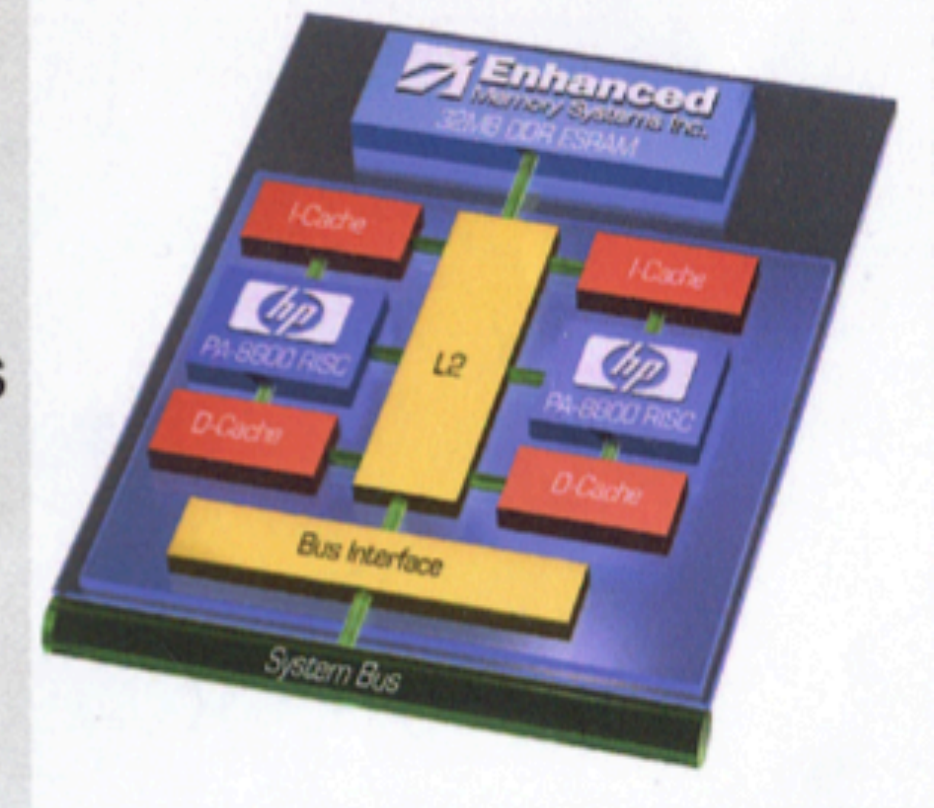
72Mb DDR ESRAM - SRAM Speed, DRAM Density


History of the DRAM

The World's Highest Density SRAMs

- Enhanced Memory and Cypress would ship 72Mbit ESRAM
- Enhanced Memory and HP would present the 72Mbit DDR ESRAM and PA-RISC at MicroProcessor Forum in 2001
- HP Announcement would drive Ramtron Stock Price Briefly from \$2 to \$30.
- By 2004, Infineon would convince Ramtron to shut-down Enhanced Memory Systems, not wanting to support a lower volume SRAM business
- HP PA-8900 would go to market with a 144Mbit DDR ESRAM-like product from IBM

- HP PA-8800 Microprocessor
 - Dual 1GHz PA-RISC Processors
 - Dual 1.5MB L1 Caches
 - 144-bit Wide L2 Cache Interface
 - 4 each 72Mb DDR ESRAM Parts
 - 13 ns Initial Latency
 - 10GB/Second Bandwidth
 - To Be Used In Most HP Workstations and Servers



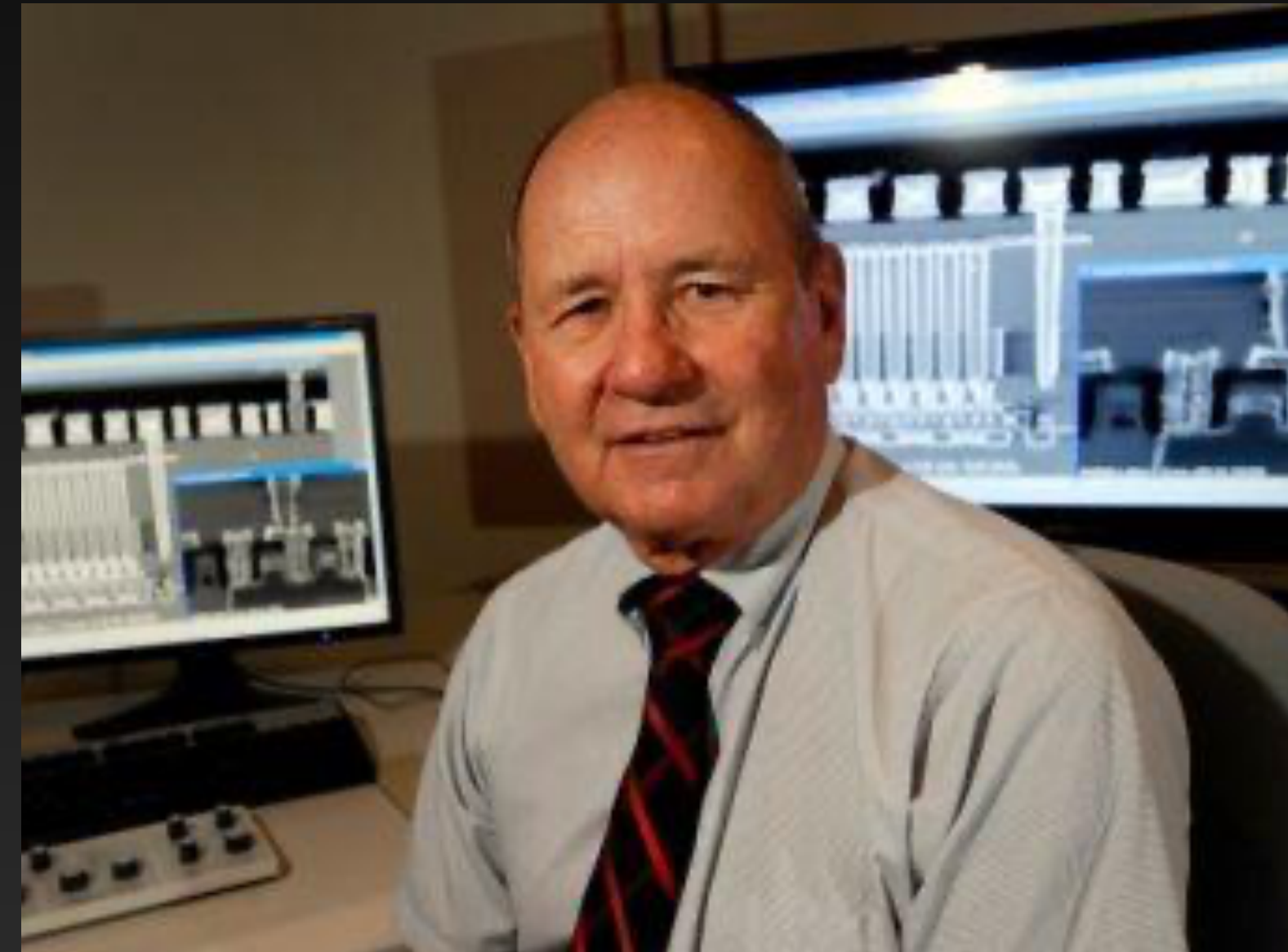
 **Enhanced**
Memory Systems Inc.

Enhanced Memory & HP Would Present PA-8800 with ESRAM at Microprocessor Forum 2001

History of the DRAM

Integrated Silicon Solutions

- United Memories continued to design the highest performance DRAM products in Colorado Springs
- United Memories President, Shef Eaton would die in a hang gliding accident
- United Memories would partner with ProMOS Technologies of Taiwan for many years developing DRAMs through 2Gb density
- In addition to standard DRAM, they developed specialty DRAM and embedded DRAM (eDRAM) designs
- One embedded DRAM was a 0.6 volt, 16Mb design with 19.5 ns cycle time
- In 2013, Integrated Silicon Solutions (ISSI), a Specialty DRAM Company, hired many of the UMI design team
- Bob Gower Retired in 2013
- UMI would continued developing DRAM until 2018
- ISSI Continues to develop specialty DRAM products in Colorado Springs today

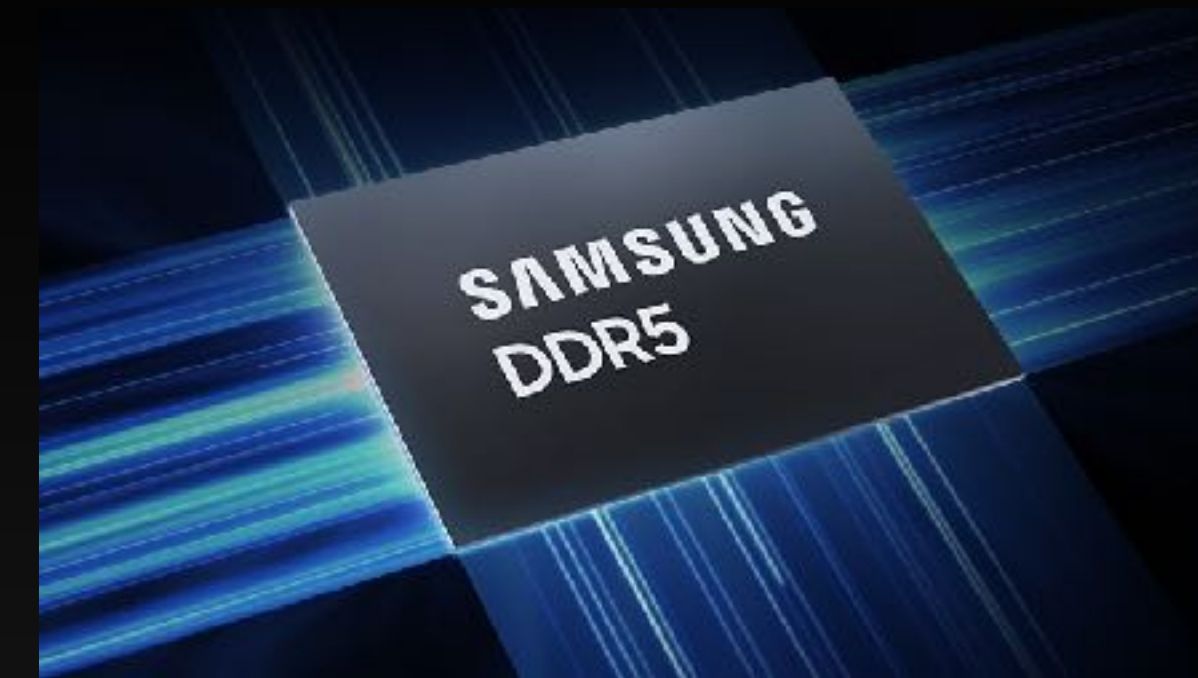


Bob Gower, CEO of United Memories

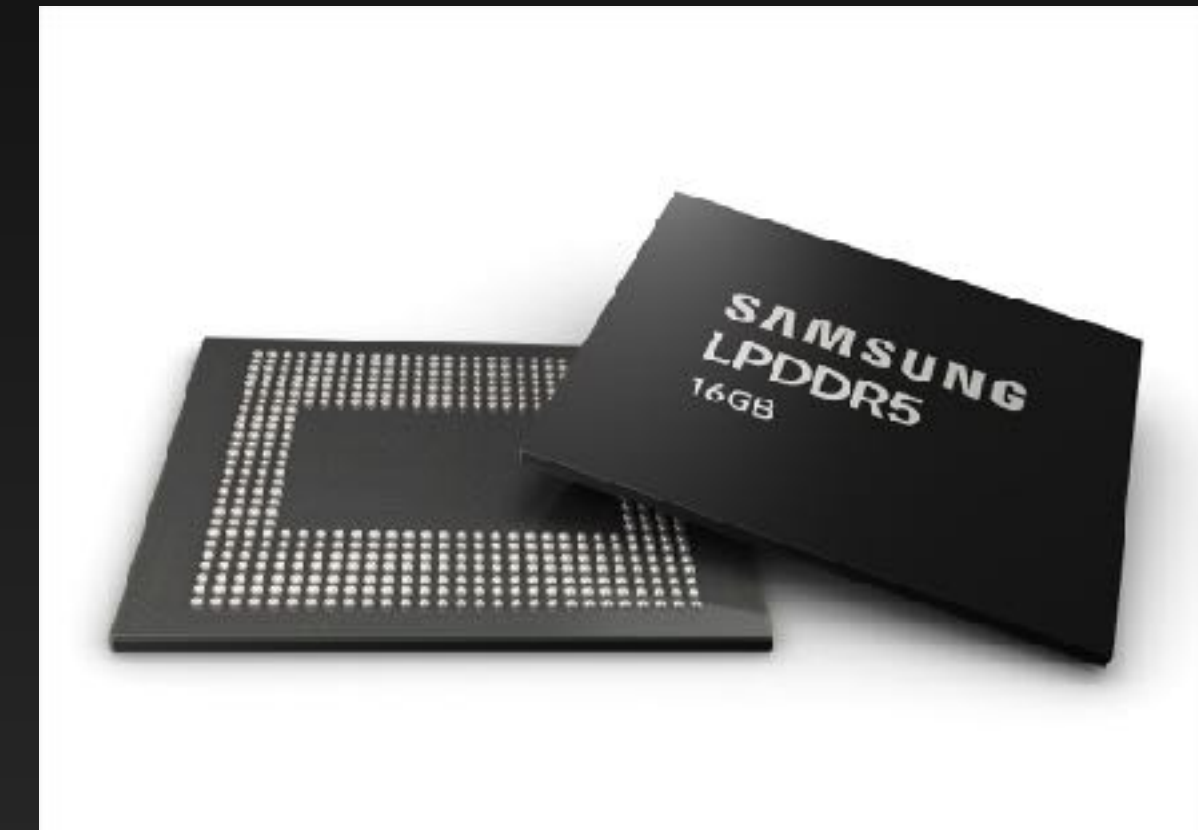
History of the DRAM

DRAM Market Today

- DRAM Products have been designed on Silicon Mountain for more than 40-years but are not longer manufactured here
- After dominating the DRAM market, Japan was superseded by Korea and Taiwan as leading manufacturers of DRAM
- Micron Technology is only US Manufacturer of DRAM
- Only 3 companies compete for the leading edge DRAM market - Samsung, SK Hynix, and Micron Technology
- DRAM density has reached 16Gb at 10 nm feature size
- The DRAM is now specialized
 - PC & Server Market - DDR3, DDR4, and DDR5
 - Mobile Market - LPDDR3, LPDDR4, LPDDR5
 - Graphics and GPU Market - GDDR6 & HBM



DDR5 DRAM for PC & Servers



LPDDR5 for Smartphones and Tablets



GDDR6 for Graphics and GPUs