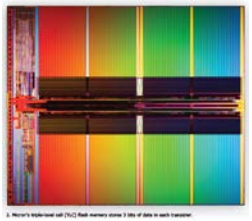
Flash: How Silicon Valley Provided the Foundation for Mobile Computing

Brian A. Berg
and an Interview with Eli Harari

25 May 2016

Brian Berg

- Owner of Berg Software Design
  - Independent consultant since 1979
- Specialty: Computer storage
  - Optical, magnetic, flash

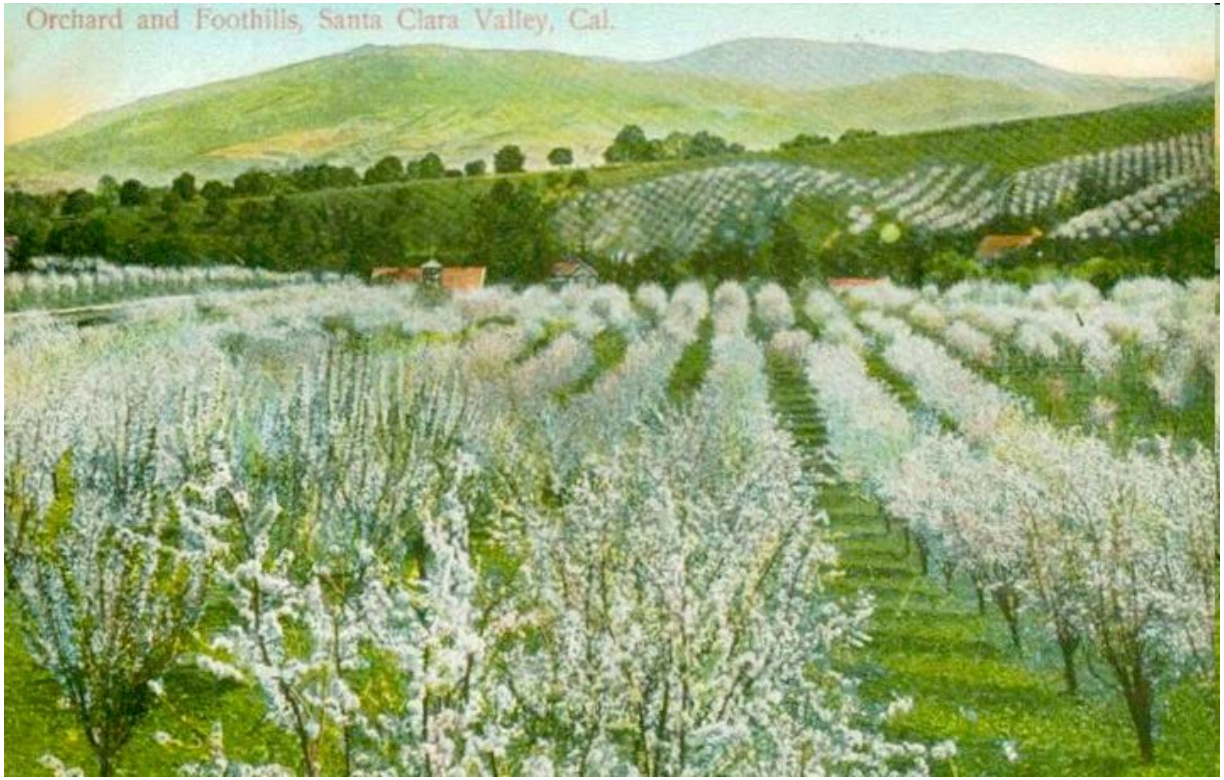


- Undergrad: Mathematics
  - Stanford Computer Engineering Masters coursework

- Consumer electronics; Intellectual Property, patents
- Conferences and events:
  - Flash Memory Summit: Technical Chair
- Active IEEE volunteer locally, in western US
- Maintains the SVDC listserver
  - 550 subscribers; promotes Saratoga Village businesses

Santa Clara Valley: "Valley of Heart's Delight"

- Also called the "Valley of the Prune" (Glen Una Ranch: world's largest prune orchard)
- 1900: Blossom Festival started where we are sitting



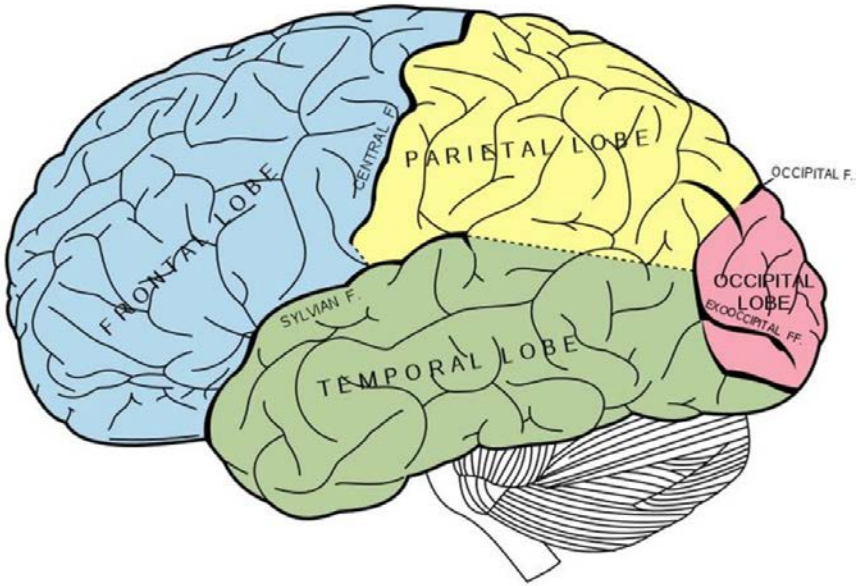
Our Program

- Background
  - Computer basics
  - Some early inventions
  - Silicon Valley and Startups
- Eli Harari Interview
  - His inventions
  - Stories
  - Mobile Computing

Computer Basics

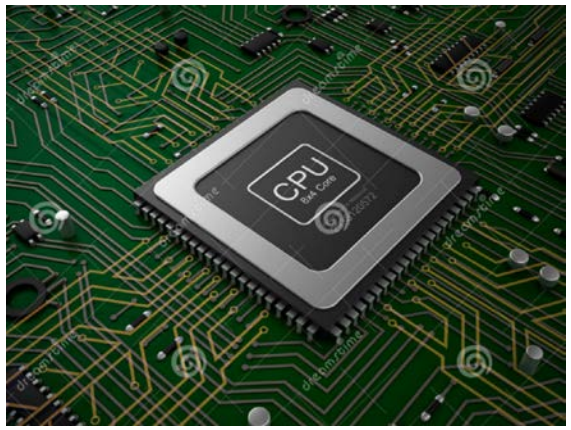
Basics: The Brain

- Key Brain Features:
  - Body Control
    - Nervous system
  - Instinct, knowledge
    - Control of body systems and organs
    - Ability to learn
  - Memory:
    - Making and saving memories



Basics: The Computer

- Computer is like a brain
- Main component is the Processor (CPU, or Central Processing Unit)
  - Operates keyboard, screen, mouse
- Runs software programs
- Controls the Memory:



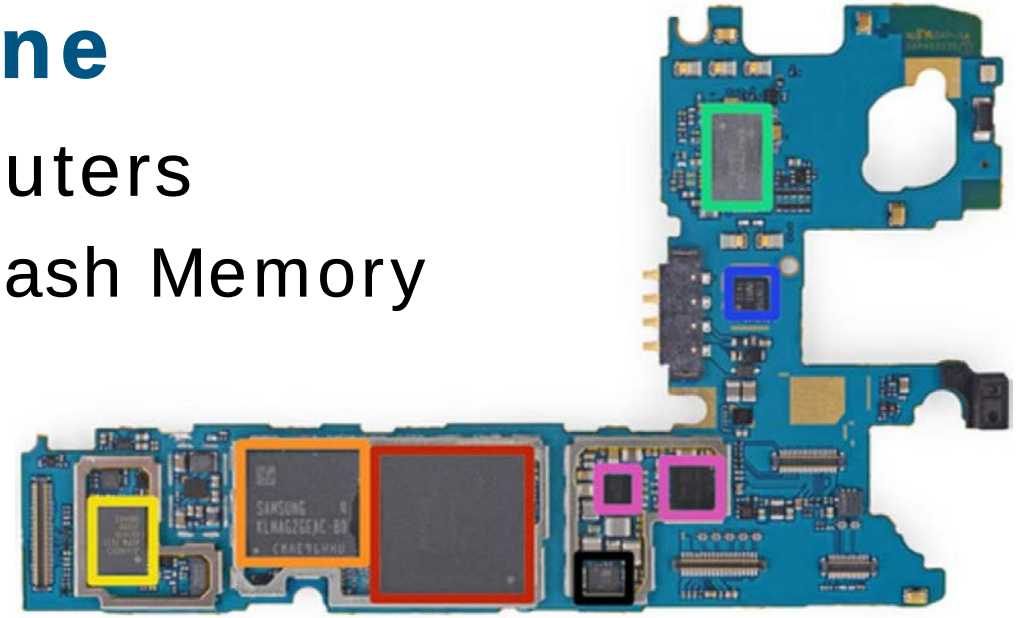
Main memory (RAM)

Disk drive

USB “Flash Drive”

Basics: Cell Phone

- Cell phones are computers
  - include CPU, RAM, Flash Memory
- Run software, e.g., Android, and “apps”
- Some cell phones sold based on Flash capacity:
  - iPhone 6 models: 16GB and 64 GB
- HP’s new cell phone has a docking station to make it usable like a desktop or laptop



Basics: The Bit

- Computers use “bits” to store any kind of data
- A bit stores a 0 or 1
- Think of a bit as a light switch:
  - If light is off, it’s a 0

  - If light is on, it’s a 1

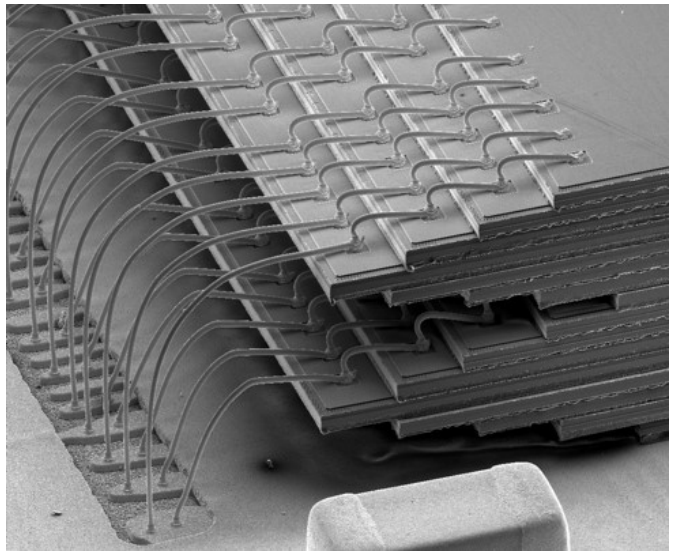
Basics: Bits and Bytes

- For 2 switches, there are 4 combinations
  - Combination #0
  - Combination #1
  - Combination #2
  - Combination #3

- 8 bits in a “byte”:
  - Combination #27

Basics: Storage

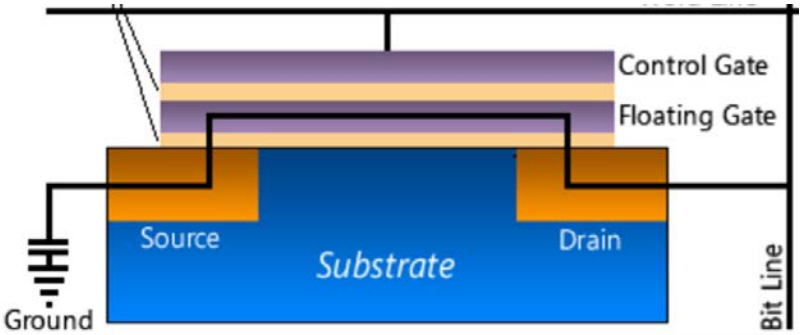
- Computer storage is described using bytes
  - 4 gigabytes GB of “RAM” (4 billion bytes)
  - 2 terabytes of disk storage (2 trillion bytes)
- Here is a flash memory card that can store 1.6 trillion bits (or 200 billion bytes): “200 GB” or “200 gigabytes”
- 11 x 15mm
- Flash cards *are computers*



BELL TELEPHONE

LABORATORIES

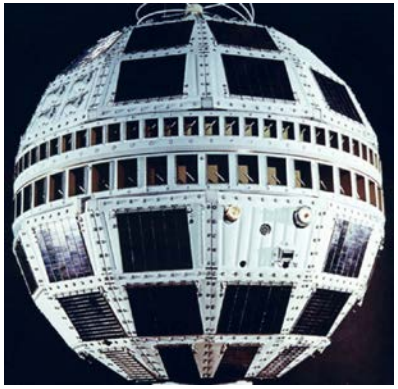
Some Key Inventions

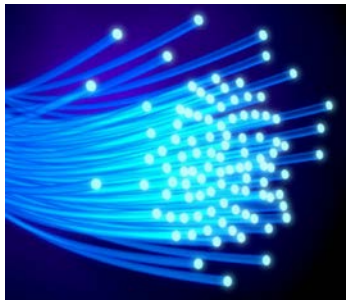


Bell Labs

BELL TELEPHONE LABORATORIES

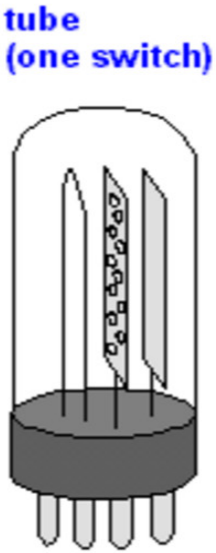
- Founded in 1925: research arm of AT&T
- Active until early 1980s
- Was world's most influential R&D entity
- Inventions include:
  - Cellular telephone networks (1947)
  - Satellites (late '50s; Telstar in 1962)
  - Laser (1964)
  - Fiber optics (late 1970s)
- Work resulted in 8 Nobel Prizes





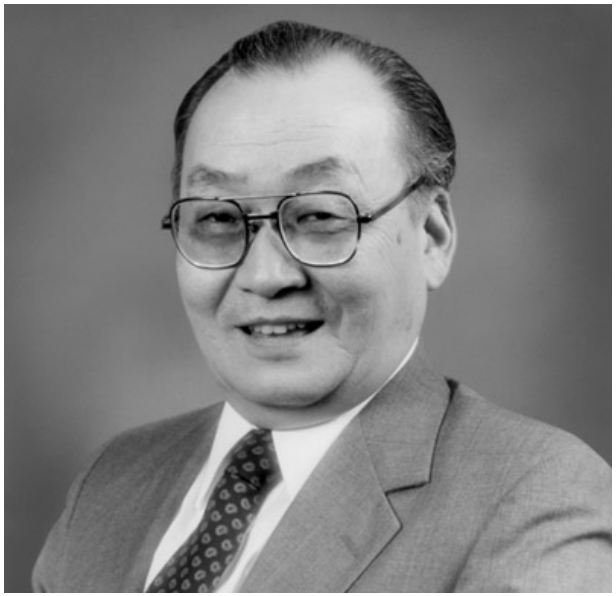
Bell Labs Inventions: 1947 - Transistor

- Invented by William Shockley (seated), John Bardeen and Walter Brattain
  - They received Nobel Prize (‘56)
- Foundation of electronics industry since early 1950s



Bell Labs Inventions: 1967 – Inspiration from a Desert

- Dawon Kahng and Simon Sze were at lunch
- Dr. Kahng ordered a piece of cake and saw the layers in the cake
- He wondered: "Could I store data in a layer of a transistor?"



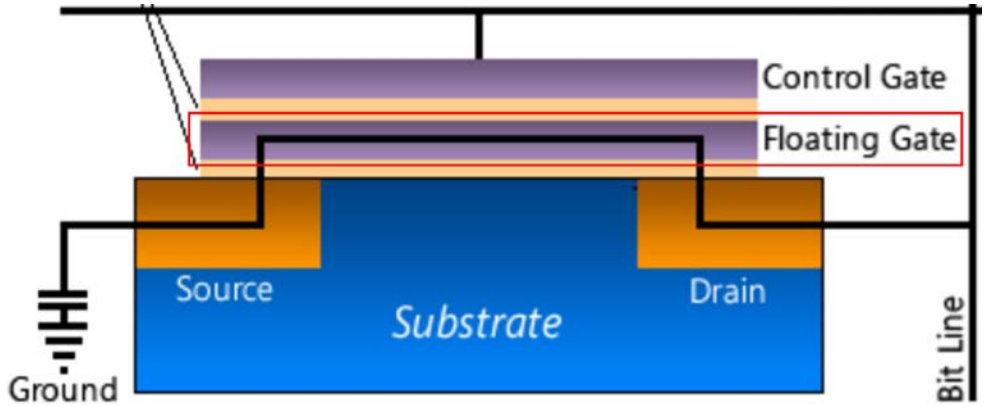
Bell Labs Inventions: 1967 – "Floating Gate"

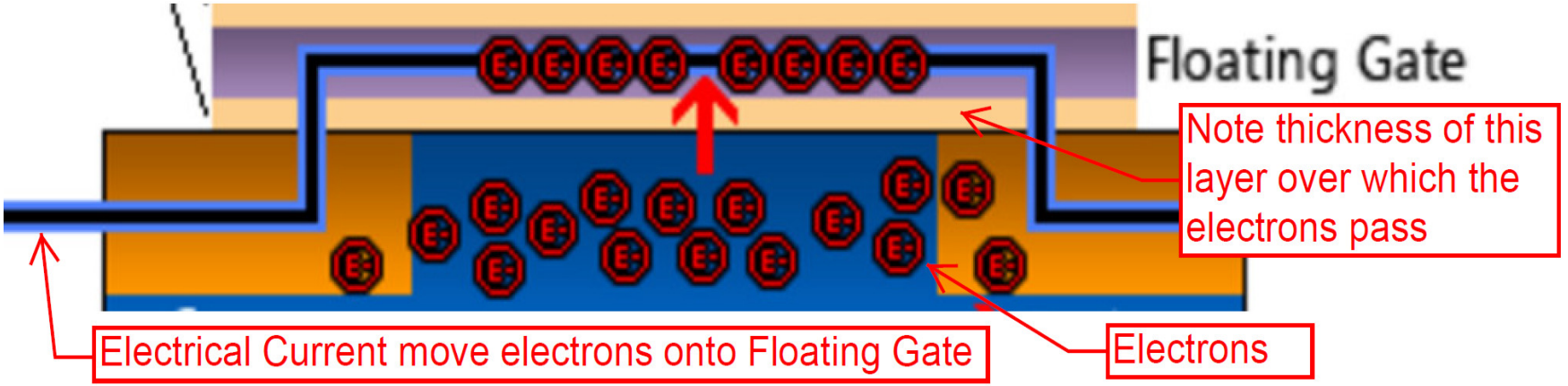
- Kahng and Sze worked on this idea
- They were successful in getting it to store data
- They called their invention a "Floating Gate"

Dr. Sze with a piece of cheesecake

Basics: “Floating Gate”

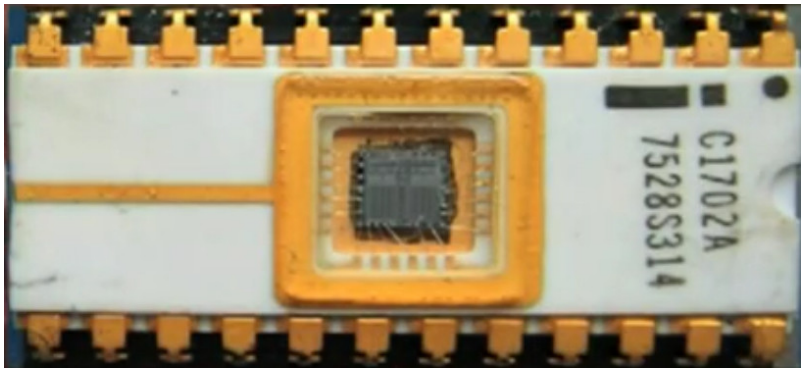
- Writing Data: shown here





- Reading Data: Sense number of electrons
- Erasing Data: remove electrons from F.G.

First Successful Floating Gate Device: EPROM



- 1970: Invented by Dov Frohman
- Erase by shining ultraviolet (UV) light
- EPROM popular for storage of software
- Hugely important for Intel's microprocessor success

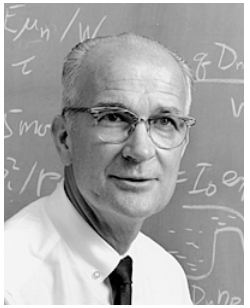
Fujio Masuoka: Flash Memory Invention

- 1984: Presented an Industry Paper
  - New use of Floating Gate
  - An entire chip could be erased at once, like the **"flash" of a camera**
- 1987: 2nd Industry Paper on Flash Memory
  - Much denser than described in 1984 paper

Toshiba

Silicon Valley, Startups and Moore's Law

1956: William Shockley Comes to California

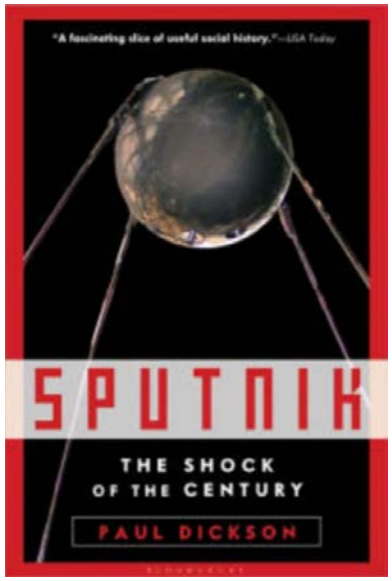


- Started Shockley Semiconductor Laboratory
- Goal: develop a new type of silicon transistor
- Recruited team of young and sharp engineers
- Shockley's strengths:
  - Good physicist
  - Recognized talent in others
- His weaknesses:
  - Terrible manager
  - Created air of paranoia

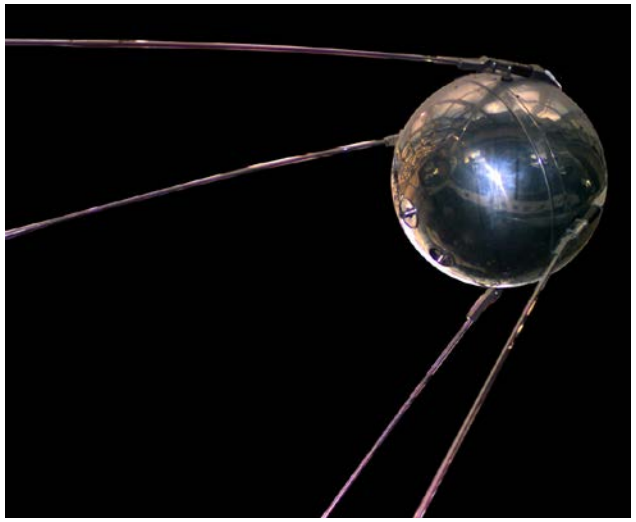
Oct. 1, 1957: First Silicon Valley Startup

- Shockley's poor management led to the "Traitorous Eight" leaving en masse
- "Venture"-funded Fairchild Semiconductor formed to create a new silicon transistor
- 4 of the 8 were:
  - Robert Noyce
  - Gordon Moore
  - Jean Hoerni
  - Eugene Kleiner (formed Kleiner Perkins)
- 3 days later...

Oct. 4, 1957: Sputnik!



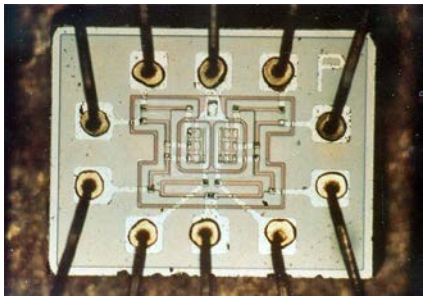
The Impact of Sputnik

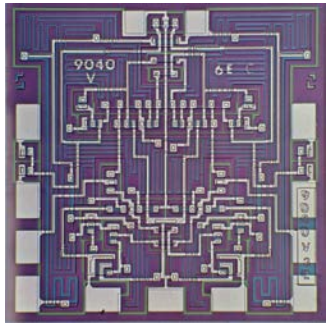


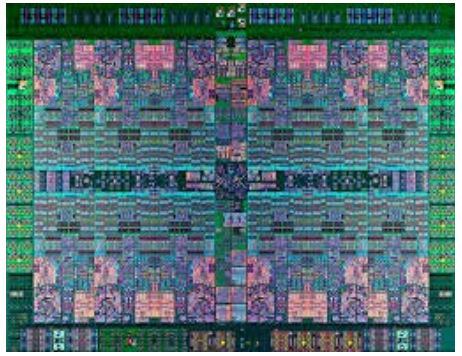
- "Space Race" between US and USSR began in earnest:
  - government began investing in science, engineering and math education
  - new missile systems and spy satellites created
  - computer technology advanced more quickly
  - July 20, 1969: US moon landing
  - Oct. 1969: "ARPANET" launched
    - became the Internet
- Fairchild had large sales to the government

Fairchild's Robert Noyce

- Strong leader, brilliant inventor
- He addressed "The Tyranny of Numbers"
  - Too many transistors!
  - 1959: Integrated Circuit: multiple transistors on a chip

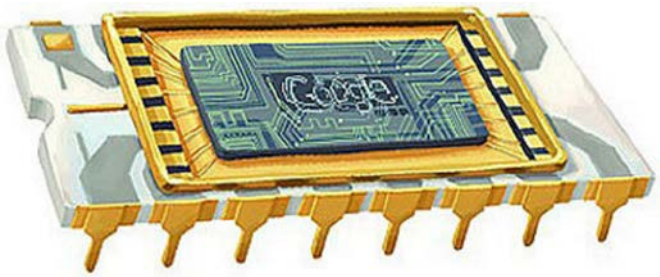






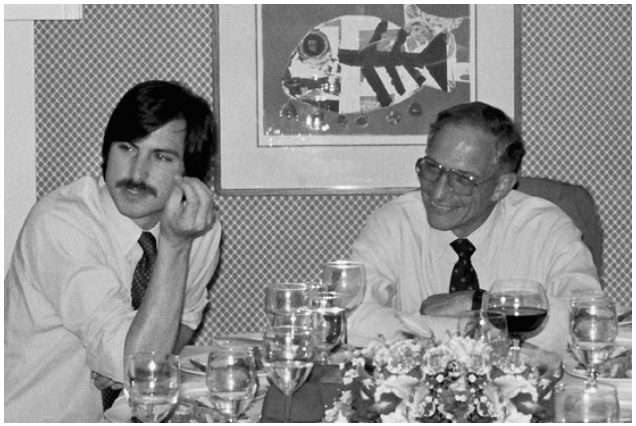
"I was trying to solve a production problem – I wasn't trying to make an integrated circuit."

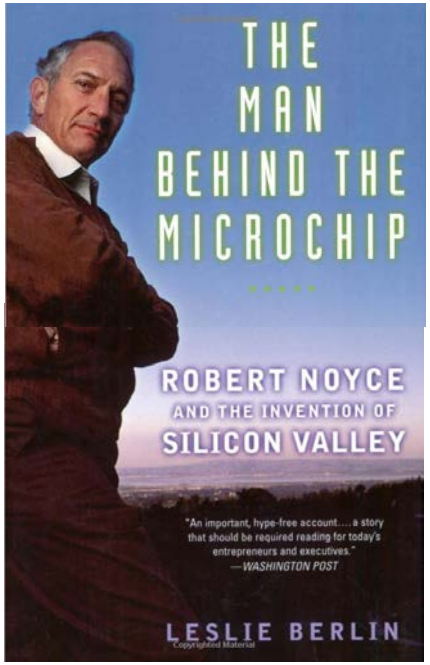
Robert Noyce (1927-1990)



- "The Mayor of Silicon Valley"
- Mentor to many, including Steve Jobs:

"Bob Noyce took me under his wing. I was ... in my 20s. He was in his early 50s. He tried to give me ... a perspective ... You can't really understand what is going on now unless you understand what came before."



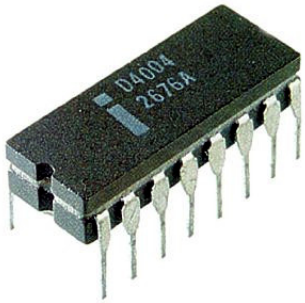


Gordon Moore: “Moore’s Law”

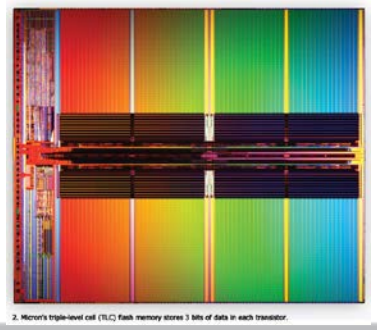
- 1965: Published what became known as “Moore’s Law”:
  - *The number of transistors that can be affordably placed on a chip will double every 2 years*

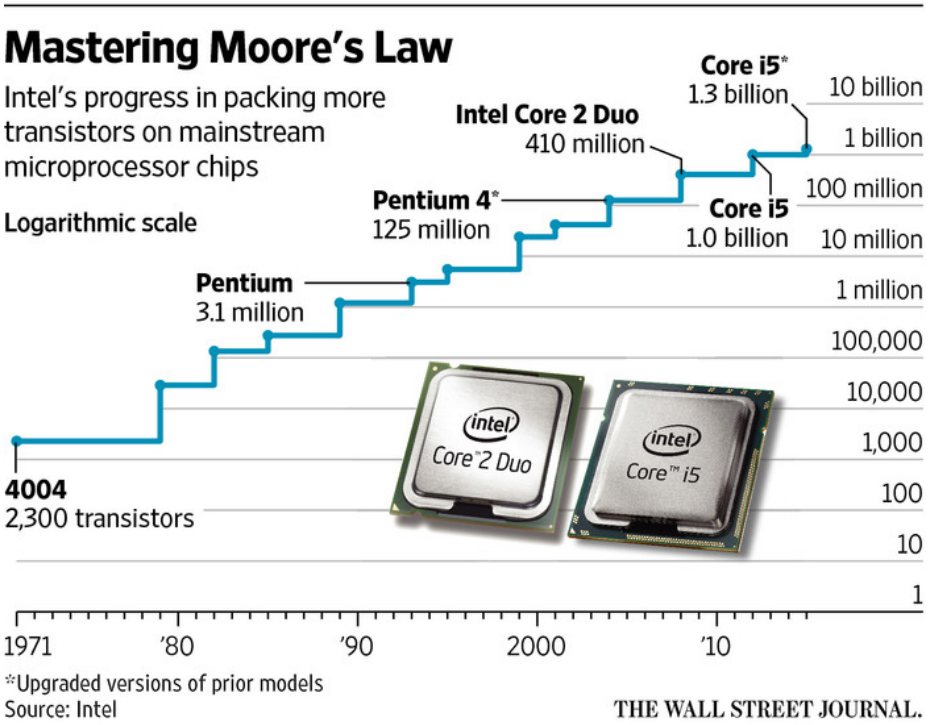
1965: Moore's Law

- Transistor count doubled 23 times in 45 years:
  - 1971: 2300 transistors (Intel 4004 microprocessor)
  - 2016: 15 billion transistors (NVIDIA Tesla P100)



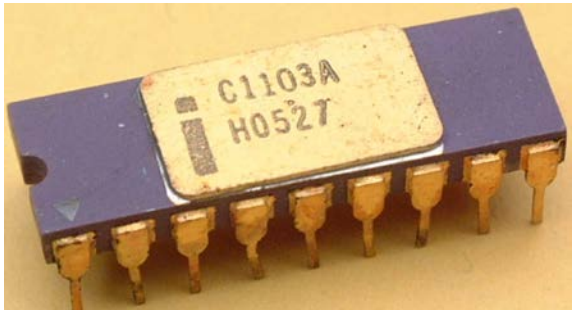
- 2015: Toshiba Flash Memory chip (256 billion bits):
  100 billion transistors

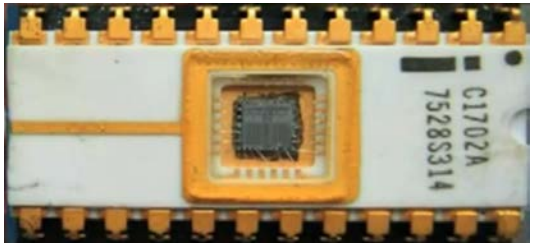




Another Silicon Valley Startup

- 1968: Gordon Moore and Robert Noyce left Fairchild to start Intel
- Goal: computer memory
- 1971: Bigger success: invention of the microprocessor
  - CPU on one chip
  - Foundation of PC revolution
- CPU sales accelerated by EPROM Floating Gate device
  - Primarily used for software programs





Dr. Eli Harari

- 1933: Parents emigrated from Poland to Palestine
- Born in Palestine
- Educated in the UK
- Came to US for PhD from Princeton Univ.
- 1973-81: Hughes and Intel
- SanDisk
  - Founded in 1988 as “SunDisk”
  - Goal: data storage in Flash
  - CEO and Board Chair
  - Retired in 2010
  - Over 150 patents

Eli Harari: 1960s

- JFK Speech (25 May 1961)
  - 55 years ago today
- Moon Landing (20 July 1969)

1969: Eli Comes to America

- Princeton University (1969-73)
- Ph.D.: 1973

PRINCETON UNIVERSITY

CHARGE TRAPPING EFFECTS IN THIN FILMS

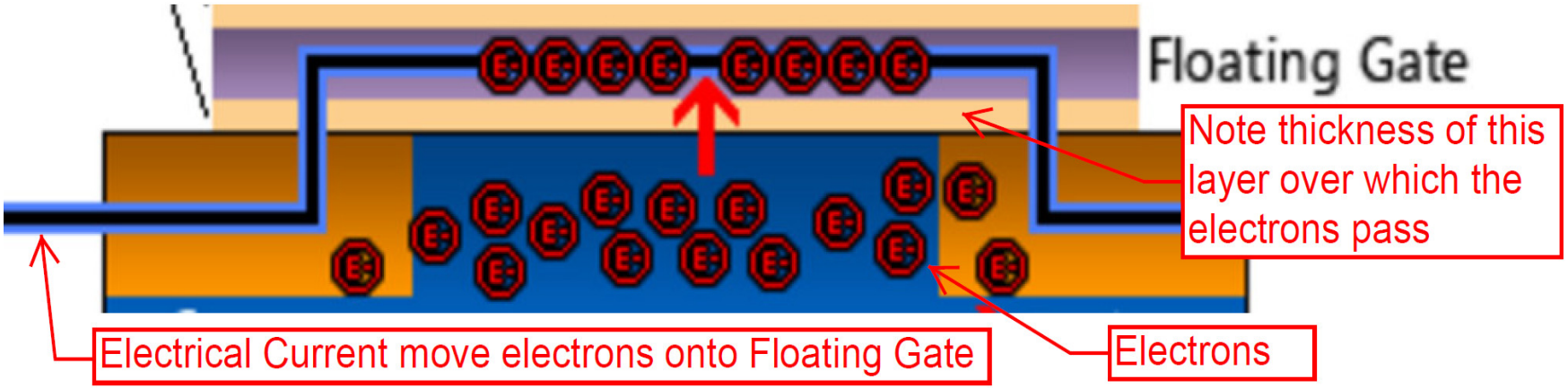
OF Al_2O_3 AND SiO_2

Eliyahou Harari

Eli Harari: Moved to California

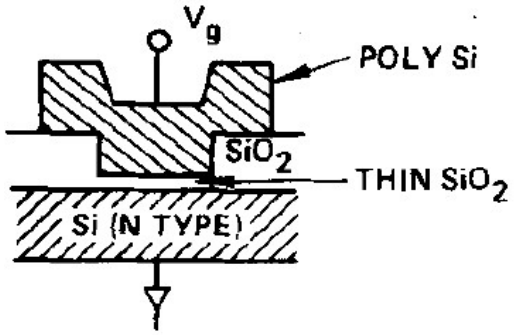
HUGHES
SEMICONDUCTOR DIVISION
Industrial Electronics Group

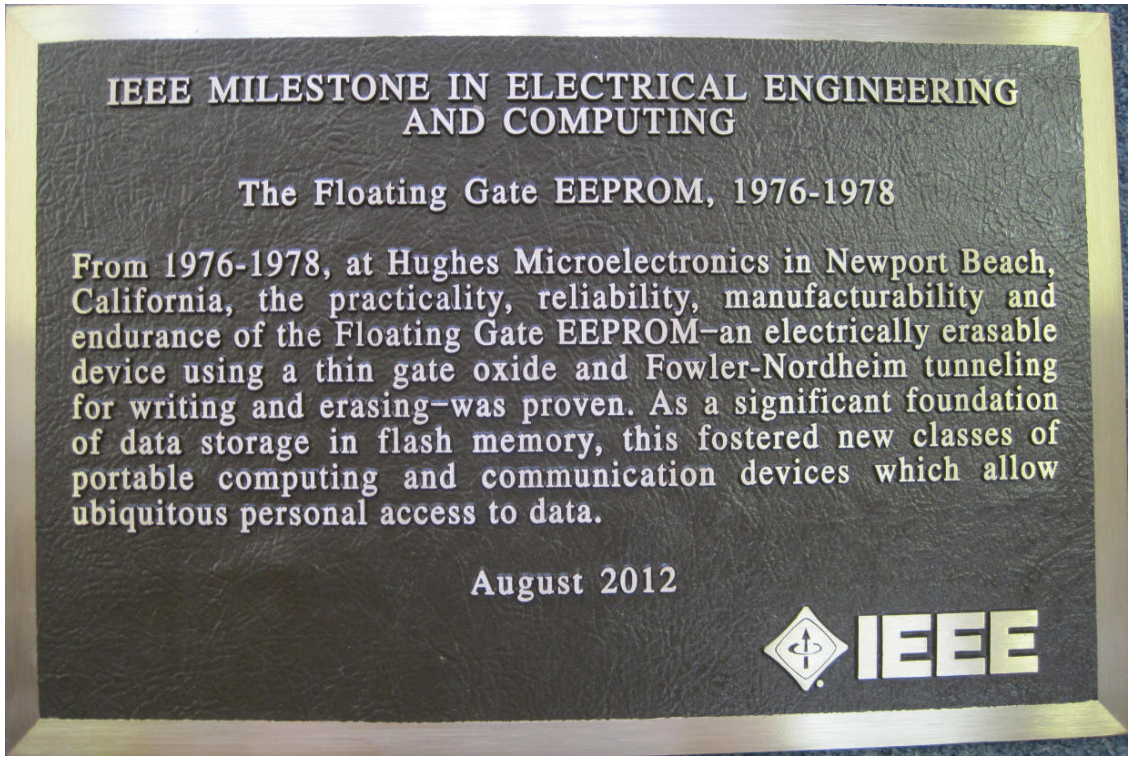
- Hughes Microelectronics, Newport Beach, CA (1973-79)
- Applied knowledge learned at Princeton to data storage using the Floating Gate



Work at Hughes on "EEPROM"

- Electrically erasable (not with UV light)
- March 1976: patent
- 1976-77: experiments
- 1977: *Journal of Applied Physics* paper
- 2012: IEEE Milestone honoring this work:
  - Reliability and Endurance
  - Flash data storage
  - "ubiquitous personal access to data"





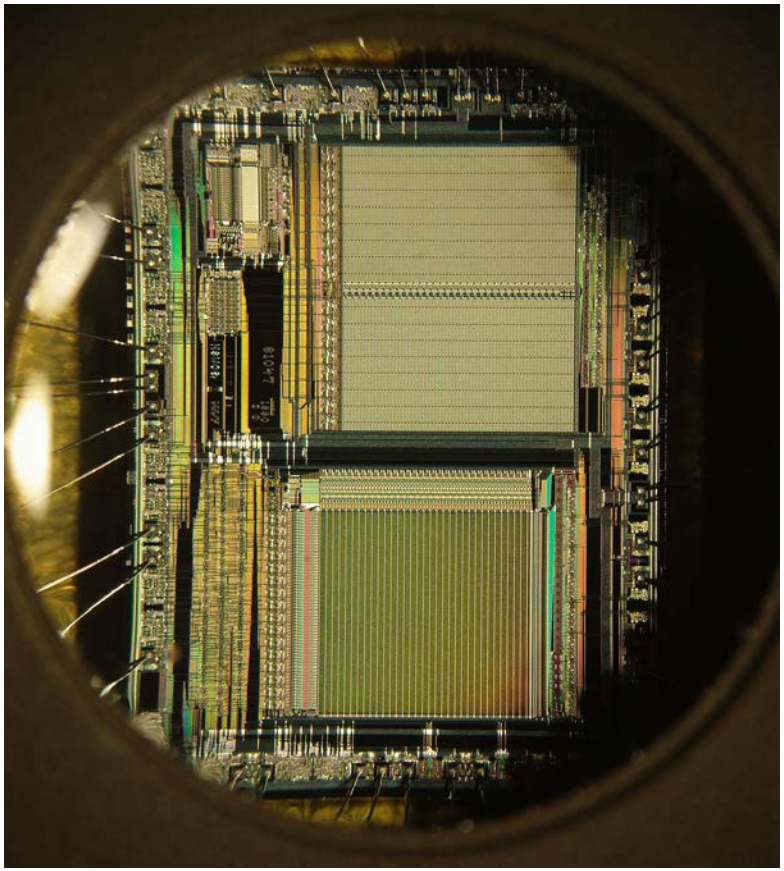
Eli Harari: IEEE Milestone Dedicated in 2012

1979-81: Eli at Intel

- Eli's work on "EEPROM" was recognized
  - Intel recruited him
- Eli had a vision for the Floating Gate:
  - **disk drive replacement**
- CEO Andy Grove rejected a project to work on this

1983-88: Waferscale Integration

- Eli co-founded this startup
  - Goal: use an entire silicon wafer to produce a single “super-chip”
  - “WaferDisc”: disk drive on an EPROM chip



1988

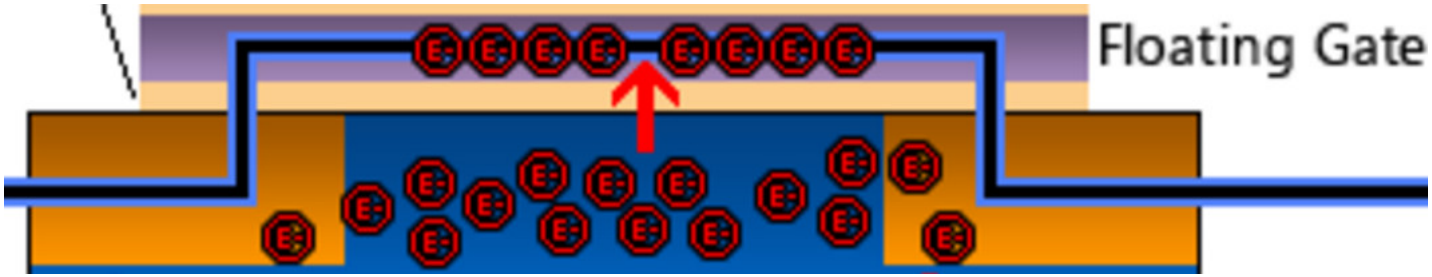
- Intel sells first Flash Memory products
  - replacement for current EPROM product
  - primarily for storing computer software
- Eli founded SunDisk (March 1, 1988)
  - New idea #1: use flash for storing data
  - New idea #2: make flash look like a disk drive

Flash-Based Disk: Pros and Cons

- Advantages v. Disk Drive
  - No mechanical parts (less likely to fail)
  - Lighter weight and shock-resistant
  - Uses less power
  - Therefore, good for mobile devices
- Disadvantages v. Disk Drive
  - Much higher cost per bit
  - However, Moore's Law will eventually make it cost-effective!

Flash is Different from a Disk

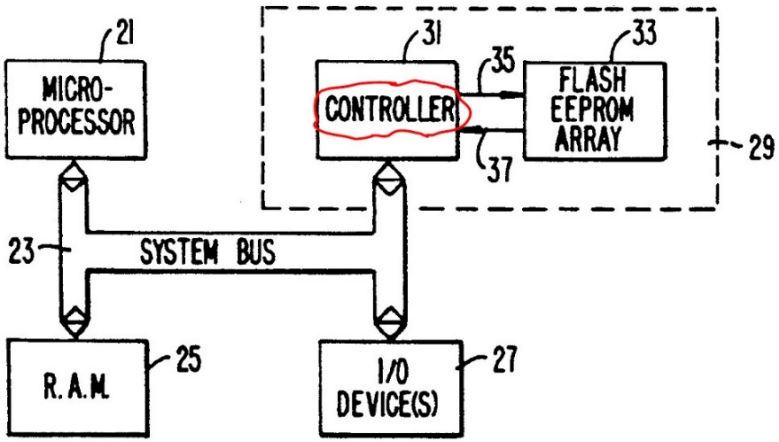
- This disk replacement has to deal with these two key characteristics of Flash
  1. Moving the electrons on and off the Floating Gates wears out the flash
  2. You need to erase before you can write



- Therefore, you need intelligence to manage the Flash Memory

Building a "Smart" Flash-Based Disk

- Intelligence to manage the flash
  - Requires a CPU and software
  - Therefore, the Flash-Based Disk is a computer
- "System-Flash" was the answer
  - Key patents filed in 1988 and 1989

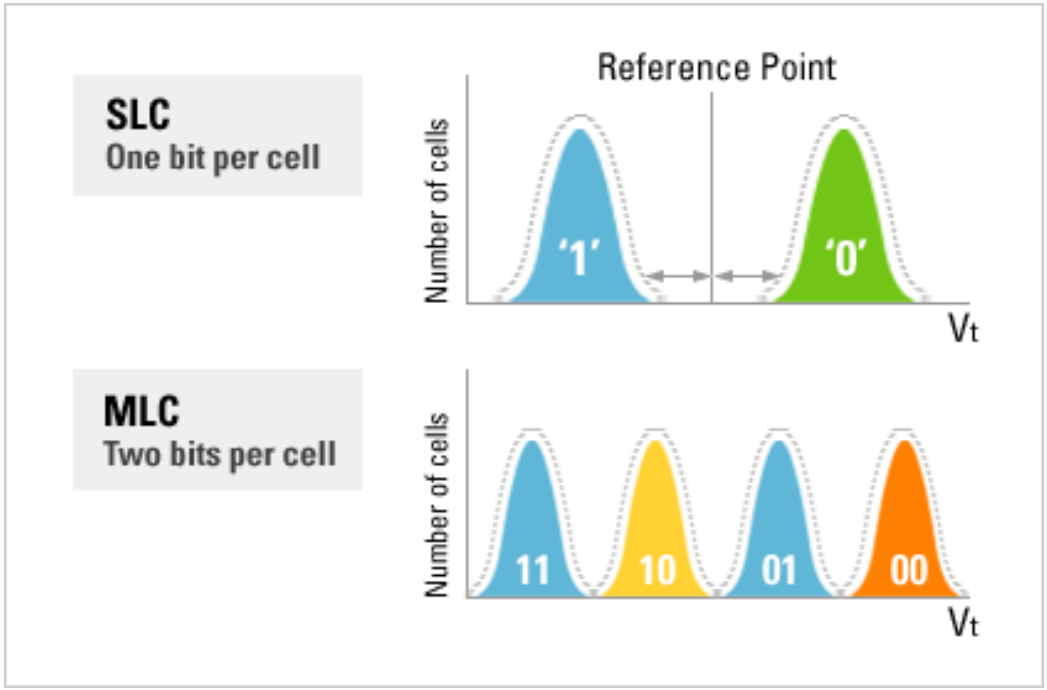


“System-Flash”: 3 Inventors

- Eli Harari:
  - Vision: (1) flash as a disk replacement and (2) data storage is the big market
  - Understood underlying physics of flash
  - SanDisk CEO: 1988-2010
- Bob Norman:
  - Disk drive design experience
  - Intelligent software design
- Sanjay Mehrotra:
  - Chip designer
  - Current SanDisk CEO

1988 Harari Invention: MLC

- MLC is “Multi-Level Cell”
- Storing more than one bit in each Floating Gate
- 2 bits doubles the capacity of flash
- Many current products store 3 bits in a Floating Gate
  - Quadruples the capacity



Stories about IBM, Kodak, Intel and Apple

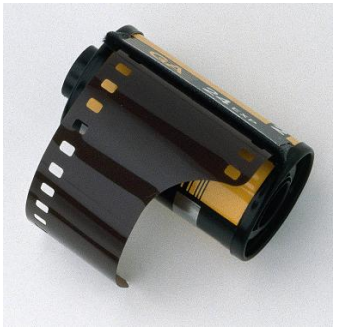
SunDisk Early Customer: IBM (1991)

- Contract for disk drive replacement for 10,000 ThinkPad laptops
  - 20MB, 2.5” device: $1000
- Requirements:
  - Plug-in disk replacement with no other changes
  - Durability of a disk drive (1 million re-write cycles)

Kodak Story

- Faith in the 35mm “cash cow”
- Management ignored engineers

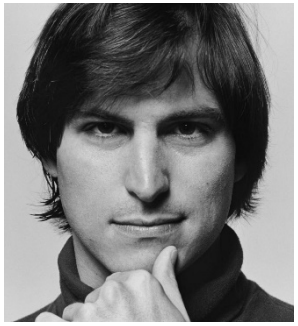
1975 Digital Camera



Intel Threatens Patent Lawsuit

- Feb. 1994:
  - Intel demanded $2 million for a cross-license patent agreement
  - (this showed that Intel needed SanDisk's patents)
- August 1994:
  - Harari responded that Intel would need to pay SanDisk instead
  - (Intel had never paid royalties to anyone)
- 1995:
  - SanDisk asked for a face-to-face meeting
  - Harari met directly with Gordon Moore

Apple iPod: From Disk to Flash



- 2000: Steve Jobs met with Eli Harari
  - Wanted Flash at cost of a disk

- Oct. **2001**: iPod introduced with
  - 5GB Toshiba 1.8” disk
- Jan. 2004 - Sept. 2005: iPod Mini with 4GB/6GB 1” disk

- Sept. **2005**: iPod Nano with
  - 4GB **flash**
- Current models: 16GB flash

Flash Memory and Mobile Computing

1990: A Vision of Mobile Computing

IEEE Electron Devices Society

Santa Clara Valley Chapter

Meeting Notice

FUTURE DIRECTIONS FOR SEMICONDUCTOR NON-VOLATILE MEMORY

Speaker: **Eli Harari**
SunDisk Corporation
Santa Clara, CA 95054.

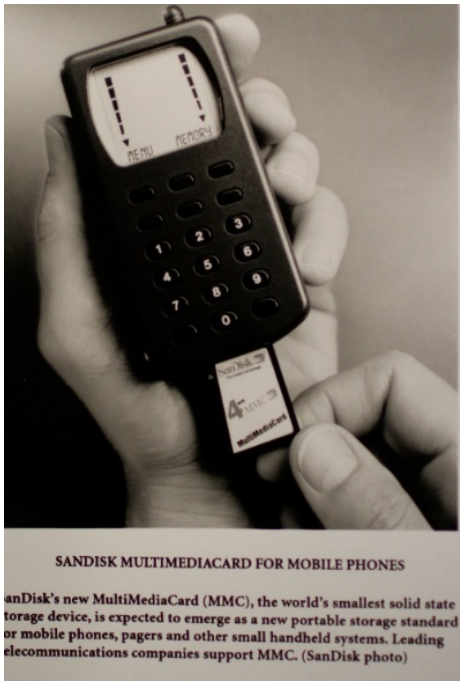
Place: Santa Clara University,
Daly Science Center
Room No. 206

Time: Tuesday, January 16th 1990, 7:30 pm.

Semiconductor non-volatile memories have in the past been an imperfect solution looking for a problem. In the coming decade, the problem, or a major market opportunity, will present itself in the form of an emerging new class of compact, portable products, such as hand-held computers, electronic notebooks, solid-state cameras, portable copiers and Fax machines, and cellular telephones. At the same time, certain types of non-volatile memory technologies, such as Flash EEPROM are at the threshold of overcoming major technological hurdles and transforming themselves from frog to prince (or king) in the new market environment.

Cellphones: The Impact of Flash

- Early ‘90s: first use of flash for storing cell phone software
- 1997/98: first use of flash cards
- 2001: first flash for data: Nokia 9100 smartphone
- 2007: iPhone introduction
- Now: cell phones use over 30% of flash production

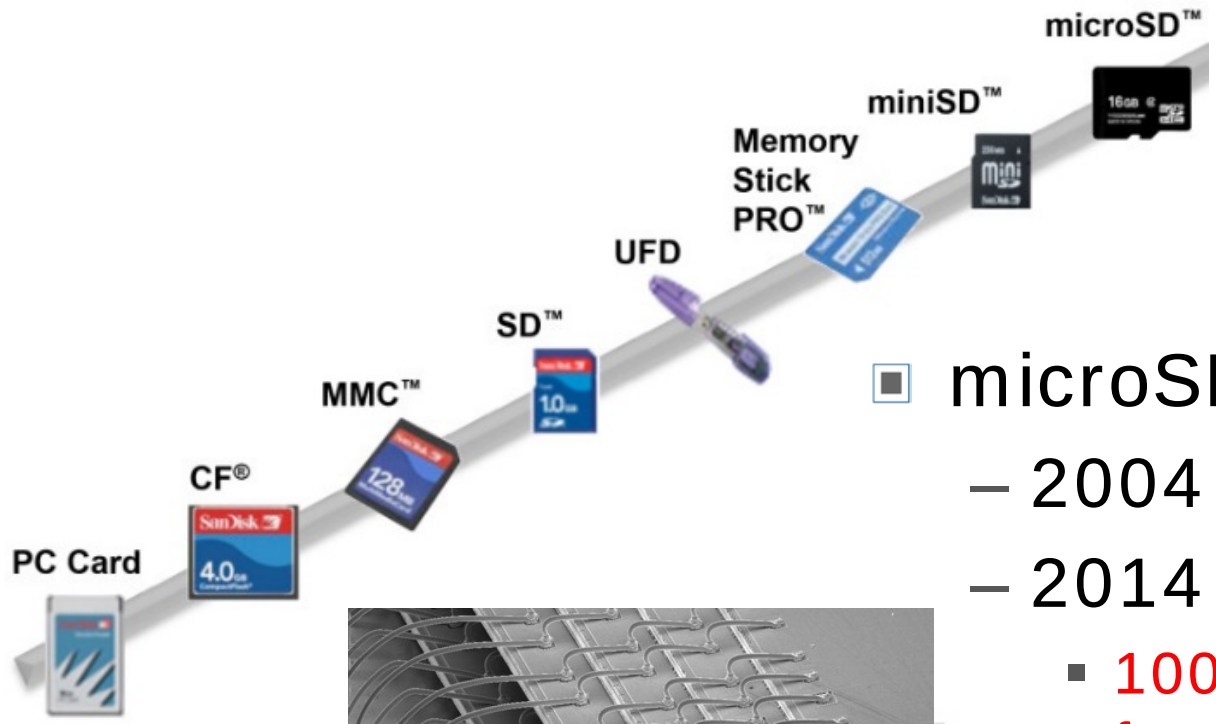


SANDISK MULTIMEDIACARD FOR MOBILE PHONES

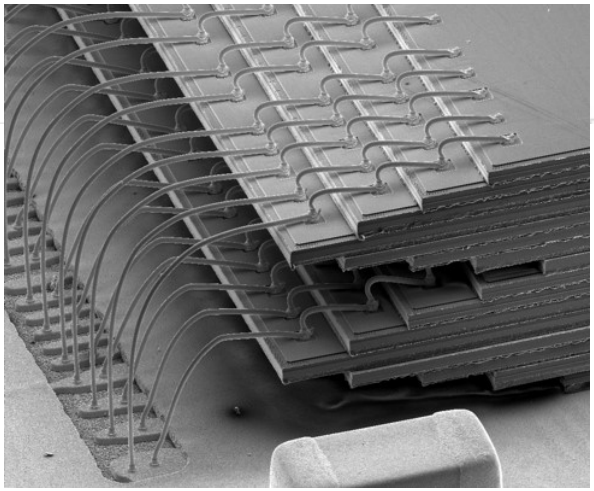
anDisk's new MultiMediaCard (MMC), the world's smallest solid state torage device, is expected to emerge as a new portable storage standard or mobile phones, pagers and other small handheld systems. Leading elecommunications companies support MMC. (SanDisk photo)

Nokia 6600

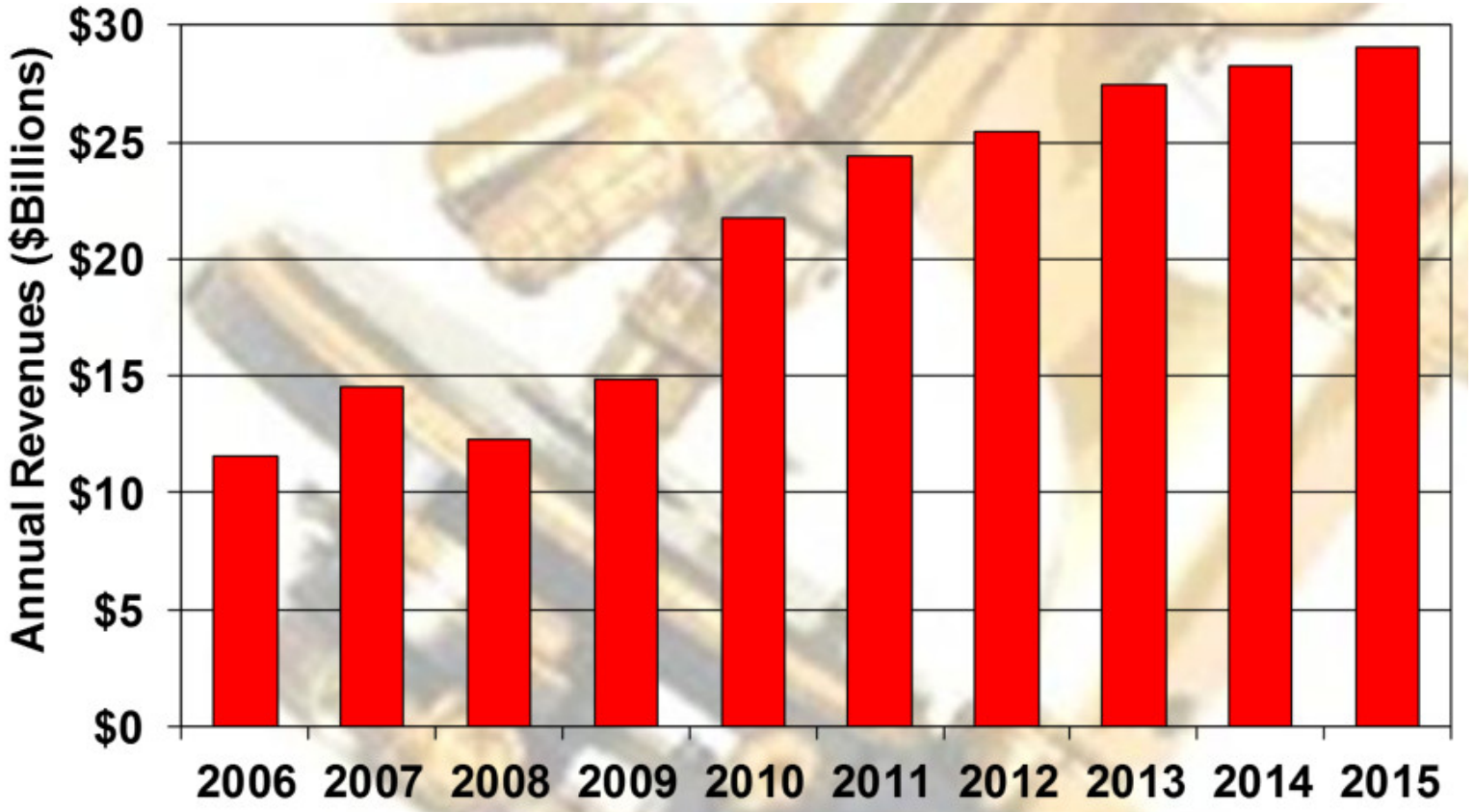
Portable Data Storage: Cards + Sticks



- microSD card
  - 2004 (128MB)
  - 2014 (128GB)
    - 1000x in 10 years: faster than Moore's Law (doubling **every year**)
  - 2015 (200GB)
    - 16 flash die + controller



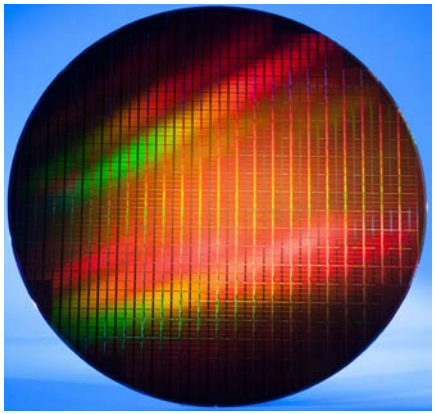
2015: Flash Sales Nearly $30 Billion

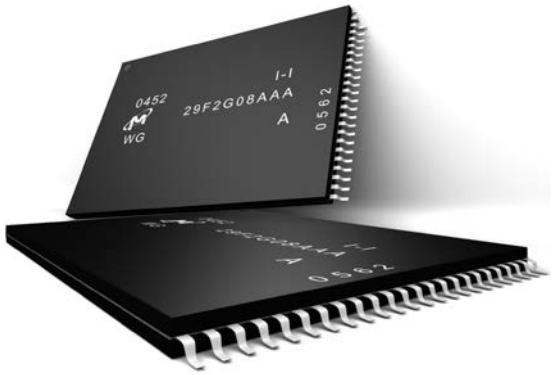


OBJECTIVE ANALYSIS – www.OBJECTIVE-ANALYSIS.com

Flash Technology Today

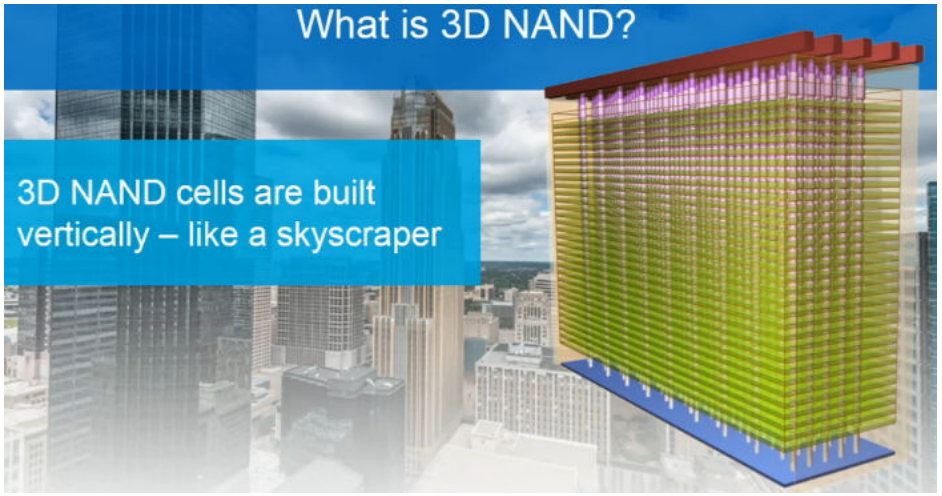
- Wafer containing about 200 “die” (Micron)





- These are sliced up and placed in a package (Micron)

- Newest flash technology uses “3D” technology
  - Largest 3D die:
    - 32 layers
    - 384 billion bits
    - ~150 billion transistors



Flash Is Ubiquitous: 3 Billion Users

- Flash used twice by your cellphone:
  - In your hand
  - Data centers are the Cloud; they are accelerated by Flash

- Internet of Things is enabled by Flash
  - wearable electronics
  - monitoring aging family members
- Upcoming technologies enabled by Flash's portability:
  - artificial intelligence (mimicking the brain)
  - machine learning
  - virtual reality

SanDisk's Story

- Disruption
  - 100,000X cost reductions over 25 years (1990-2015)
  - obsoleting old technology:





- Success thanks to Moore's Law

SanDisk Today

- Over 5,000 patents
  - Patent licensing revenues: over $5 Billion
- Company bought for $16.2 Billion two weeks ago:

WESTERN DIGITAL COMPLETES ACQUISITION OF SANDISK, CREATING A GLOBAL LEADER IN STORAGE TECHNOLOGY

MAY 12, 2016

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Dr. Eli Harari – Awards

- 2004 Ernst & Young Entrepreneur of the Year Lifetime Award
- 2006 IEEE Reynold B. Johnson Data Storage Device Tech. Award
- 2008 GSA (Global Semiconductor Alliance) Dr. Morris Chang Exemplary Leadership Award
- 2011: Consumer Electronics Hall of Fame
- Member: National Academy of Engineering

Dr. Eli Harari – Awards

- 2009: IEEE Robert N. Noyce Medal for Exceptional Contributions to the Microelectronics Industry

2014: National Medal of Technology and Innovation

- "For invention and commercialization of Flash storage technology to enable ubiquitous data in consumer electronics, mobile computing, and enterprise storage."
- Obama: "One month after Neil Armstrong landed on the moon, Eli Harari came to America from Israel to study the effects of radiation on electronics in space."