EE330
Integrated Electronics
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The Semiconductor Process

The Transistor, Reliability and Yield, Review of Basic Statistical Concepts, A Brief History
History 101

- 1925, 1935 → The concept of the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) Transistor Proposed (Lilienfield and Heil)
- 1947 → The Bipolar Junction Transistor (BJT) conceived and experimentally verified (Bardeen, Bratin and Shockley of Bell Labs)
- 1959 → Jack Kilby from Texas Instruments, and Bob Noyce from Fairchild invent the Integrated Circuit
- 1963 → Wanless from Fairchild experimentally verifies the MOS Gate
1926 - Field Effect Semiconductor Device Concepts Patented

Julius Lilienfeld files a patent describing a three-electrode amplifying device based on the semiconducting properties of copper sulfide. Attempts to build such a device continue through the 1930s.

Polish-American physicist and inventor Julius E. Lilienfeld filed a patent in 1926, "Method and Apparatus for Controlling Electric Currents," in which he proposed a three-electrode structure using copper-sulfide semiconductor material. Today this device would be called a field-effect transistor. While working at Cambridge University in 1934, German electrical engineer and inventor Oskar Heil filed a patent on controlling current flow in a semiconductor via capacitive coupling at an electrode - essentially a field-effect transistor. Although both patents were granted, no records exist to prove that Heil or Lilienfeld actually constructed functioning devices.

Heil, O. "Improvements in or relating to electrical amplifiers and other control arrangements and devices," British Patent No. 439, 457 (Filed March 5, 1935. Issued December 6, 1935).

http://www.computerhistory.org/semiconductor/timeline/1926-field.html
UNITED STATES PATENT OFFICE

JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Application filed October 8, 1926, Serial No. 140,363, and in Canada October 22, 1925.

Jan. 28, 1930. J. E. LILIENFELD 1,745,175

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926
March 7, 1933.

J. E. LILIENTHOLD

DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928

3 Sheets-Sheet 1

Fig. 1.

Fig. 2.
History 101: Naming the Transistor

◆ From the group at Bell Labs

“We have called it the transistor, T-R-A-N-S-I-S-T-O-R, because it is resistor or semiconductor device which can amplify electrical signals as they are transferred through it from input to output terminals. It is, if you will, the electrical equivalent of a vacuum tube amplifier. But there the similarity ceases. It has no vacuum, no filament, no glass tube. It is composed entirely of cold, solid substances.”
History 101

William Shockley

http://www.time.com/time/time100/scientist/profile/shockley03.html
William Shockley
He fathered the transistor and brought the silicon to Silicon Valley but is remembered by many only for his noxious racial views
By GORDON MOORE

The transistor was born just before Christmas 1947 when John Bardeen and Walter Brattain, two scientists working for William Shockley at Bell Telephone Laboratories in Murray Hill, N.J., observed that when electrical signals were applied to contacts on a crystal of germanium, the output power was larger than the input. Shockley was not present at that first observation. And though he fathered the discovery in the same way Einstein fathered the atom bomb, by advancing the idea and pointing the way, he felt left out of the momentous occasion.

Shockley, a very competitive and sometimes infuriating man, was determined to make his imprint on the discovery. He searched for an explanation of the effect from what was then known of the quantum physics of semiconductors. In a remarkable series of insights made over a few short weeks, he greatly extended the understanding of semiconductor materials and developed the underlying theory of another, much more robust amplifying device — a kind of sandwich made of a crystal with varying impurities added, which came to be known as the junction transistor. By 1951 Shockley's co-workers made his semiconductor sandwich and demonstrated that it behaved much as his theory had predicted.
William Shockley
He fathered the transistor and brought the silicon to Silicon Valley but is remembered by many only for his noxious racial views

By GORDON MOORE

Not content with his lot at Bell Labs, Shockley set out to capitalize on his invention. In doing so, he played a key role in the industrial development of the region at the base of the San Francisco Peninsula. It was Shockley who brought the silicon to Silicon Valley.

In February 1956, with financing from Beckman Instruments Inc., he founded Shockley Semiconductor Laboratory with the goal of developing and producing a silicon transistor. He chose to establish this start-up near Palo Alto, where he had grown up and where his mother still lived. He set up operations in a storefront — little more than a Quonset hut — and hired a group of young scientists (I was one of them) to develop the necessary technology. By the spring of 1956 he had a small staff in place and was beginning to undertake research and development.

This new company, financed by Fairchild Camera & Instrument Corp., became the mother organization for several dozen new companies in Silicon Valley. Nearly all the scores of companies that are or have been active in semiconductor technology can trace the technical lineage of their founders back through Fairchild to the Shockley Semiconductor Laboratory. Unintentionally, Shockley contributed to one of the most spectacular and successful industry expansions in history.
William Shockley

He fathered the transistor and brought the silicon to Silicon Valley but is remembered by many only for his noxious racial views

By GORDON MOORE

Editor's note:

In 1963 Shockley left the electronics industry and accepted an appointment at Stanford. There he became interested in the origins of human intelligence. Although he had no formal training in genetics or psychology, he began to formulate a theory of what he called dysgenics. Using data from the U.S. Army’s crude pre-induction IQ tests, he concluded that African Americans were inherently less intelligent than Caucasians — an analysis that stirred wide controversy among laymen and experts in the field alike.

(Fairchild was formed in 1957 – Moore and Noyce were 2 or 8 co-founders)
EXEMPLARY CLAIM

1. A semiconductor device comprising:
   a. a wafer of semiconductor material having two major faces;
   b. said wafer being so shaped as to define a plurality of regions within said wafer and adjacent to one of said major faces;
   c. at least some of said regions being electrically isolated within said wafer from others of said regions;
   d. said regions having at least one portion thereof extending to said one major face;
   e. at least some of said portions having selected locations on said one major face for electrical contact to said region;
   f. an insulating material on said one major face of the wafer excluding at least said selected locations;
   g. at least one electrically conductive area in contact with said insulating material and spaced from said wafer thereby;
   h. said electrically conductive area being disposed in cooperative relationship with respect to a selected one of said isolated regions so as to provide the electrical function of a discrete electrical circuit component; and
   i. a plurality of metallic interconnections providing electrically conductive paths between said selected locations on different ones of said regions and between another selected one of said locations and said electrically conductive area.

4 Claims, 33 Drawing Figures
History 101

Jack Kilby
There are few men whose insights and professional accomplishments have changed the world. Jack Kilby is one of these men. His invention of the monolithic integrated circuit - the microchip - some 45 years ago at Texas Instruments (TI) laid the conceptual and technical foundation for the entire field of modern microelectronics. It was this breakthrough that made possible the sophisticated high-speed computers and large-capacity semiconductor memories of today's information age.

Mr. Kilby grew up in Great Bend, Kansas. With B.S. and M.S. degrees in electrical engineering from the Universities of Illinois and Wisconsin respectively, he began his career in 1947 with the Centralab Division of Globe Union Inc. in Milwaukee, developing ceramic-base, silk-screen circuits for consumer electronic products.

In 1958, he joined TI in Dallas. During the summer of that year working with borrowed and improvised equipment, he conceived and built the first electronic circuit in which all of the components, both active and passive, were fabricated in a single piece of semiconductor material half the size of a paper clip. The successful laboratory demonstration of that first simple microchip on September 12, 1958, made history.

Jack Kilby went on to pioneer military, industrial, and commercial applications of microchip technology. He headed teams that built both the first military system and the first computer incorporating integrated circuits. He later co-invented both the hand-held calculator and the thermal printer that was used in portable data terminals.
Robert Norton Noyce was born December 12, 1927 in Burlington, Iowa. A noted visionary and natural leader, Robert Noyce helped to create a new industry when he developed the technology that would eventually become the microchip. Noted as one of the original computer entrepreneurs, he founded two companies that would largely shape today’s computer industry—Fairchild Semiconductor and Intel.

Bob Noyce’s nickname was the "Mayor of Silicon Valley." He was one of the very first scientists to work in the area -- long before the stretch of California had earned the Silicon name -- and he ran two of the companies that had the greatest impact on the silicon industry: Fairchild Semiconductor and Intel. He also invented the integrated chip, one of the stepping stones along the way to the microprocessors in today's computers.

Noyce, the son of a preacher, grew up in Grinnell, Iowa. He was a physics major at Grinnell College, and exhibited while there an almost baffling amount of confidence. He was always the leader of the crowd. This could turn against him occasionally -- the local farmers didn’t approve of him and weren’t likely to forgive quickly when he did something like steal a pig for a college luau. The prank nearly got Noyce expelled, even though the only reason the farmer knew about it was because Noyce had confessed and offered to pay for it.

While in college, Noyce’s physics professor Grant Gale got hold of two of the very first transistors ever to come out of Bell Labs. Gale showed them off to his class and Noyce was hooked. The field was young, though, so when Noyce went to MIT in 1948 for his Ph.D., he found he knew more about transistors than many of his professors.
After a brief stint making transistors for the electronics firm Philco, Noyce decided he wanted to work at Shockley Semiconductor. In a single day, he flew with his wife and two kids to California, bought a house, and went to visit Shockley to ask for a job -- in that order.

As it was, Shockley and Noyce's scientific vision -- and egos -- clashed. When seven of the young researchers at Shockley semiconductor got together to consider leaving the company, they realized they needed a leader. All seven thought Noyce, aged 29 but full of confidence, was the natural choice. So Noyce became the eighth in the group that left Shockley in 1957 and founded Fairchild Semiconductor.

Noyce was the general manager of the company and while there invented the integrated chip -- a chip of silicon with many transistors all etched into it at once. Fairchild Semiconductor filed a patent for a semiconductor integrated circuit based on the planar process on July 30, 1959. That was the first time he revolutionized the semiconductor industry. He stayed with Fairchild until 1968, when he left with Gordon Moore to found Intel. At Intel he oversaw Ted Hoff's invention of the microprocessor -- that was his second revolution.

At both companies, Noyce introduced a very casual working atmosphere, the kind of atmosphere that has become a cultural stereotype of how California companies work. But along with that open atmosphere came responsibility. Noyce learned from Shockley's mistakes and he gave his young, bright employees phenomenal room to accomplish what they wished, in many ways defining the Silicon Valley working style was his third revolution.
1971 → Intel Introduces 4004 microprocessor (2300 transistors, 10u process)
The Metal Oxide Semiconductor (MOS) Transistor

The Ideal Switch Level View
Modelling of Electronic Devices

- Each electronic device has corresponding models that can be used to describe its behavior

- These models can vary depending on the desired:
  - Complexity
  - Accuracy
  - Insight
  - Application

- It is wise to use the simplest model that can provide acceptable results for any given application
There are two types of MOS transistors → n-channel and p-channel

In an n-channel transistor, the current is conducted by electrons, while in a p-channel it is conducted by holes

The transistor is a complicated device and can operate in many different modes, and will have unique behavior in each mode

Each mode will have its unique model that describes its behavior

We will gradually go through all the different modes and discover how the transistor can be used to build useful circuits
The MOS Transistor: n-Channel

The n-channel MOSFET is a semiconductor device used in electronics. It consists of a channel region, which can be n-type or p-type, and a gate electrode. The channel region is sandwiched between the source and drain terminals. The gate is used to control the conductivity of the channel.

Complete Symmetry in construction between Drain and Source

Designer always works with top view

Cross-Sectional View

Top View

Symbol

n-type
n+-type
p-type
p+-type
SiO₂ (insulator)
POLY (conductor)
The MOS Transistor: n-Channel

- Behavioral Description of Basic Operation
  - If $V_{GS}$ is large, short circuit exists between drain and source
  - If $V_{GS}$ is small (near zero), open circuit exists between drain and source

![Diagram of n-channel MOSFET](image)
The MOS Transistor: n-Channel

Equivalent Circuit for n-channel MOSFET

Source assumed to be connected to ground
G=0 means the gate voltage is close to ground
G=1 means the gate voltage is close to $V_{DD}$

This is the first model we have for the n-channel MOSFET \text{→} An Ideal Switch!
The MOS Transistor: n-Channel

◆ Equivalent Circuit for n-channel MOSFET → An Ideal Switch

Mathematically

\[ I_D = 0 \quad \text{if} \quad V_G \quad \text{is low} \quad (V_{GSn} \quad \text{is small}) \quad \rightarrow \quad \text{The Switch is off} \]

\[ V_{DS} = 0 \quad \text{if} \quad V_G \quad \text{is high} \quad (V_{GSn} \quad \text{is large}) \quad \rightarrow \quad \text{The Switch is on} \]

When the switch is off, it behaves like an open circuit (infinite resistance)
When the switch is on it behaves like a short circuit (zero resistance)
The MOS Transistor: p-Channel

Complete Symmetry in construction between Drain and Source
The MOS Transistor: p-Channel

- Behavioral Description of Basic Operation

- If $V_{GS}$ is large (negative), short circuit exists between drain and source → Large negative $V_{GS}$ is the same as large positive $V_{SG}$
- If $V_{GS}$ is small (near zero), open circuit exists between drain and source
The MOS Transistor: p-Channel

Equivalent Circuit for p-channel MOSFET

Source assumed to be connected to $V_{DD}$
G=0 means the gate voltage is close to ground
G=1 means the gate voltage is close to $V_{DD}$

This is the first model we have for the p-channel MOSFET → A Complementary Ideal Switch!
The MOS Transistor: p-Channel

◆ Equivalent Circuit for p-channel MOSFET \( \rightarrow \) A Complementary Ideal Switch

Mathematically

\[ I_D = 0 \quad \text{if } V_G \text{ is high (} |V_{GSp}| \text{ is small, } V_{SGp} \text{ is small)} \rightarrow \text{The Switch is off} \]

\[ V_{DS} = 0 \quad \text{if } V_G \text{ is low (} |V_{GSp}| \text{ is large, } V_{SGp} \text{ is large)} \rightarrow \text{The Switch is on} \]

When the switch is off, it behaves like an open circuit (infinite resistance)
When the switch is on it behaves like a short circuit (zero resistance)
The MOS Transistor: Comparison
The MOS Transistor: Summary

- Models for the n-channel and p-channel MOS devices have been developed
  - Termed the ideal switch-level model
  - Several other models will be developed later
  - Invariably use simplest model that is justifiable
  - Will introduce better models only when needed

- Symbols have been introduced for the two basic transistors
  - Other symbols will be introduced later
Basic Logic Circuits

An Application to the MOS Transistor
So the MOS transistor can be used as an ideal switch, how is that useful?

Logic Circuits!!

We will present a brief description of logic circuits based upon simple models and qualitative description of processes.

We will discuss process technology needed to develop better models.

We will provide more in-depth discussion of logic circuits based upon better device models.
Boolean versus Continuous Notation

- Voltage Axis is Continuous between 0V and $V_{DD}$, while Boolean axis is discrete with only two points

- Most logic circuits characterized by the relationship between the Boolean input/output variables though these correspond to voltage ranges on the continuous voltage axis
From now on, and for logic circuits purposes:
- A signal with a voltage level close to $V_{DD}$, will be referred to as logic “high” or simply “1”
- A signal with a voltage level close to Ground, will be referred to as logic “low” or simply “0”
- Note that “1” and “0” in this context do not describe actual voltage, but logic levels