Transistors

"The Transistor was probably the most important invention of the 20th Century..."

The American Institute of Physics

The Nobel Prize in Physics 1956

William Bradford Shockley
USA
Semiconductor Laboratory of Beckman Instruments, Inc.
Mountain View, CA, USA
b. 1910
(in London, United Kingdom)
d. 1989
1/3 of the prize

John Bardeen
USA
University of Illinois
Urbana, IL, USA
b. 1908
d. 1991
1/3 of the prize

Walter Houser Brattain
USA
Bell Telephone Laboratories
Murray Hill, NJ, USA
b. 1902
d. 1987
1/3 of the prize
Transistors

Zhores I. Alferov, Russian, 70, A.F. Ioffe Physico-Technical Institute, St. Petersburg
Herbert Kroemer, German-born American, 72, Univ. of California, Santa Barbara
Jack S. Kilby, American, 76, Texas Instruments, Dallas

The prize is being awarded with one half jointly to:
ZHORES I. ALFEROV, and HERBERT KROEMER for developing semiconductor heterostructures used in high-speed- and opto-electronics
and one half to:
JACK ST. CLAIR KILBY for his part in the invention of the integrated circuit
Transistors

First Transistor, 1947
(Schokley, Bardeen, Brattain)

First Integrated Circuit, 1958
(Jack Kilby)

Intel’s IC 2007
Each die incorporates around 1.9 billion transistor in a single chip
What are transistors for?
Transistor is a solid-state switch

Mechanical switch

3V 120V

Solar triggered switch (opto-switch)

Thermo-switch
What are transistors for?

Transistor is a logical gate – a heart of computer

\[ X = \overline{A+B+C+D} \]
What are transistors for?

Transistor is an amplifier (audio, video, microwave)
Bipolar Junction Transistors (BJT)

A Bipolar Transistor essentially consists of a pair of PN Junction Diodes that are joined back-to-back.
Field-Effect Transistor (FET) principles

Lots of electrons

No electrons

Lots of electrons – high S-D current

No electrons – no S-D current
Any FET is essentially a capacitor.

Let the area of the capacitor plates be $A$.
The induced charge $Q$ can be expressed in terms of field-induced carrier concentration as

$$Q = q \times A \times \Delta n_S,$$

where $q = 1.6 \times 10^{-19}$ C is the electron charge,

$\Delta n_S$ is the **CHANGE of surface (aka sheet) electron concentration** due to induced electrons,

$\Delta n_S = Q / (q \times A)$;

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**What is the sheet concentration?**
The bulk charge density, $n$ the layer thickness, $a$;
then the sheet concentration,

$$n_S = n \times a \quad [\text{m}^{-2}] \text{ or } [\text{cm}^{-2}]$$
Induced charge in FETs (cont.)

For the PLAIN CAPACITOR, \( C = \varepsilon \varepsilon_0 \times A/d \)

\[
Q = C \times V = \varepsilon \varepsilon_0 \times A \times V/d,
\]

The charge per unit area, \( Q_1 = \varepsilon \varepsilon_0 \times V/d \)

The induced concentration of \textit{electrons} in the \textit{top (metal) plate}:

\[
\Delta n_{SM} = -\varepsilon \varepsilon_0 \times V/(q \times d) < 0 \text{ (depletion)}
\]

in the \textit{bottom (semiconductor) plate}:

\[
\Delta n_S = \varepsilon \varepsilon_0 \times V/(q \times d) > 0 \text{ (accumulation)}
\]
Induced charge estimation

\[ \varepsilon = \varepsilon_r \times \varepsilon_0; \]  
For the gap filled with dielectric, \( \varepsilon_r = 10; \)  
\( \varepsilon_0 = 8.85 \times 10^{-14} \text{ F/cm}; \)

Let \( d = 0.1 \ \mu\text{m}; \) \( V = 10 \ \text{V}; \)

\[ \Delta n_S = \varepsilon_r \varepsilon_0 \times V/(q \times d) \]

\[ |\Delta n_s| \approx 5.53 \times 10^{12} \ \text{cm}^{-2}; \]

We now compare the induced and the equilibrium electron concentrations.

For 1 \( \mu\text{m} \) thick semiconductor film with \( N_D = 10^{16} \ \text{cm}^{-3}; \)

\[ n_S \approx 10^{16} \times 10^{-4} = 10^{12} \ \text{cm}^{-2}; \]

For 1 \( \mu\text{m} \) thick metal film, \( n_{SM} \approx 10^{23} \times 10^{-4} = 10^{19} \ \text{cm}^{-2} >> |\Delta n_S|; \)

- No conductivity modulation in the metal plate
- Significant conductivity modulation in the semiconductor film
- In this example, the semiconductor film with the equilibrium surface electron concentration of 5\( \times \) \( 10^{12} \ \text{cm}^{-2} \) would be completely depleted by applying 10 V at the gate
Metal - Oxide - Semiconductor FET (MOSFET)

The gate-channel insulator is made out of dielectric \((\text{SiO}_2)\), \(\varepsilon = 3.9\)
The gate-channel insulator consists of the p-n junction DEPLETION REGION

For GaAs, $\varepsilon \sim 12$; for GaN $\varepsilon \sim 9$. 
Metal-Semiconductor FET (MESFET)

The gate is formed by Schottky barrier to the semiconductor layer. The gate-channel insulator consists of the Schottky DEPLETION REGION. MESFET is very similar to the JFET.
The Heterostructure Field-Effect Transistor (HFET)

The channel is formed by doping

The channel is formed by 2D electron gas (2DEG) in the UNDOPED material

JFET, MOSFET, MESFET

HFET