

# Sources of noise in transistor



## **SOURCE OF NOISE IN TRANSISTOR FOR DIFFERENT CONFIGURATION**

### **Abstract-**

Here in this term paper, I am going to discuss the history of the transistors, its importance and its limitations. The term paper is on the sources of noise in transistors for different configurations.

### **HISTORY**

#### **A replica of the first working transistor.**

The first patent for the field-effect transistor principle was filed in Canada by Austrian-Hungarian physicist Julius Edgar Lilienfeld on October 22, 1925, but Lilienfeld did not publish any research articles about his devices. In 1934 German physicist Dr. Oskar Heil patented another field-effect transistor.

On 17 November 1947 John Bardeen and Walter Brattain, at AT&T Bell Labs, observed that when electrical contacts were applied to a crystal of germanium, the output power was larger than the input. William Shockley saw the potential in this and worked over the next few months greatly expanding the knowledge of semiconductors and is considered by many to be the “father” of the transistor. The term was coined by John R. Pierce.

### **IMPORTANCE**

The transistor is considered by many to be the greatest invention of the twentieth-century, or as one of the greatest. It is the key active component in practically all modern electronics. Its importance in today's society rests on its ability to be mass produced using a highly automated process (fabrication) that achieves astonishingly low per-transistor costs.

Although several companies each produce over a billion individually-packaged (known as discrete) transistors every year, the vast majority of transistors produced are in integrated circuits (often shortened to IC, microchips or simply chips) along with diodes, resistors, capacitors and other electronic components to produce complete electronic circuits. A logic gate consists of about twenty transistors whereas an advanced microprocessor, as of 2006, can use as many as 1.7 billion transistors (MOSFETs). “ About 60 million transistors were built this year [2002] ... for [each] man, woman, and child on Earth.”

The transistor's low cost, flexibility and reliability have made it a ubiquitous device. Transistorized mechatronic circuits have replaced electromechanical devices in controlling appliances and machinery. It is often easier and cheaper to use a standard microcontroller and write a computer program to carry out a control function than to design an equivalent mechanical control function.[1]

## **USAGE**

The bipolar junction transistor, or BJT, was the first transistor invented, and through the 1970s, was the most commonly used transistor. Even after MOSFETs became available, the BJT remained the transistor of choice for many analog circuits such as simple amplifiers because of their greater linearity and ease of manufacture. Desirable properties of MOSFETs, such as their utility in low-power devices, usually in the CMOS configuration, allowed them to capture nearly all market share for digital circuits; more recently MOSFETs have captured most analog and power applications as well,

including modern clocked analog circuits, voltage regulators, amplifiers, power transmitters, motor drivers, etc.

BJT used as an electronic switch, in grounded-emitter configuration.

### **How a transistor works**

Amplifier circuit, standard common-emitter configuration.

Simple circuit using a transistor.

### **Operation graph of a transistor**

The essential usefulness of a transistor comes from its ability to use a small signal applied between one pair of its terminals to control a much larger signal at another pair of terminals. This property is called “ gain”. A transistor can control its output in proportion to the input signal; this is called an “ amplifier”. Or, the transistor can be used to turn current on or off in a circuit like an electrically controlled “ switch”, where the amount of current is determined by other circuit elements.

The two types of transistors have slight differences in how they are used in a circuit. A bipolar transistor has terminals labelled base, collector and emitter. A small current at base terminal can control or switch a much larger current between collector and emitter terminals. For a field-effect transistor, the terminals are labelled gate, source, and drain, and a voltage at the gate can control a current between source and drain.

The image to the right represents a typical bipolar transistor in a circuit. Charge will flow between emitter and collector terminals depending on the current in the base. Since internally the base and emitter connections

behave like a semiconductor diode, a voltage drop develops between base and emitter while the base current exists. The size of this voltage depends on the material the transistor is made from, and is referred to as  $V_{BE}$ .

Transistors are commonly used as electronic switches, for both high power applications including switched-mode power supplies and low power applications such as logic gates.

It can be seen from the graph that once the base voltage reaches a certain level, shown at B, the current will no longer increase with increasing  $V_{BE}$  and the output will be held at a fixed voltage.[dubious – discuss] The transistor is then said to be saturated. Hence, values of input voltage can be chosen such that the output is either completely off, or completely on. The transistor is acting as a switch, and this type of operation is common in digital circuits where only “ on” and “ off” values are relevant.

### **TRANSISTOR AS AN AMPLIFIER**

The above common emitter amplifier is designed so that a small change in voltage in ( $V_{in}$ ) changes the small current through the base of the transistor and the transistor’s current amplification combined with the properties of the circuit mean that small swings in  $V_{in}$  produce large changes in  $V_{out}$ .

It is important that the operating parameters of the transistor are chosen and the circuit designed such that as far as possible the transistor operates within a linear portion of the graph, such as that shown between A and B, otherwise the output signal will suffer distortion.

Various configurations of single transistor amplifier are possible, with some providing current gain, some voltage gain, and some both.

From mobile phones to televisions, vast numbers of products include amplifiers for sound reproduction, radio transmission, and signal processing. The first discrete transistor audio amplifiers barely supplied a few hundred milliwatts, but power and audio fidelity gradually increased as better transistors became available and amplifier architecture evolved.

Modern transistor audio amplifiers of up to a few hundred watts are common and relatively inexpensive.

Some musical instrument amplifier manufacturers mix transistors and vacuum tubes in the same circuit, as some believe tubes have a distinctive sound.

Prior to the development of transistors, vacuum (electron) tubes (or in the UK “ thermionic valves” or just “ valves”) were the main active components in electronic equipment.

### **ADVANTAGES**

The key advantages that have allowed transistors to replace their vacuum tube predecessors in most applications are:

- I. Small size and minimal weight, allowing the development of miniaturized electronic devices.
- II. Highly automated manufacturing processes, resulting in low per-unit cost.

- III. Lower possible operating voltages, making transistors suitable for small, battery-powered applications.
- IV. No warm-up period for cathode heaters required after power application.
- V. Lower power dissipation and generally greater energy efficiency.
- VI. Higher reliability and greater physical ruggedness.
- VII. Extremely long life. Some transistorized devices produced more than 30 years ago are still in service.
- VIII. Complementary devices available, facilitating the design of complementary-symmetry circuits, something not possible with vacuum tubes.
- IX. Insensitivity to mechanical shock and vibration, thus avoiding the problem of microphonics in audio applications. [2]

### **LIMITATIONS**

- I. Silicon transistors do not operate at voltages higher than about 1, 000 volts (SiC devices can be operated as high as 3, 000 volts). In contrast, electron tubes have been developed that can be operated at tens of thousands of volts.
- II. High power, high frequency operation, such as used in over-the-air television broadcasting, is better achieved in electron tubes due to improved electron mobility in a vacuum.

III. On average, a higher degree of amplification linearity can be achieved in electron tubes as compared to equivalent solid state devices, a characteristic that may be important in high fidelity audio reproduction.

IV. Silicon transistors are much more sensitive than electron tubes to an electromagnetic pulse, such as generated by a nuclear explosion.

V. Semiconductor material: germanium, silicon, gallium arsenide, silicon carbide, etc.

VI. Structure: BJT, JFET, IGFET (MOSFET), IGBT, “ other types”

VII. Polarity: NPN, PNP (BJTs); N-channel, P-channel (FETs)

VIII. Maximum power rating: low, medium, high

IX. Maximum operating frequency: low, medium, high, radio frequency (RF), microwave (The maximum effective frequency of a transistor is denoted by the term  $f_T$ , an abbreviation for “ frequency of transition”. The frequency of transition is the frequency at which the transistor yields unity gain).

X. Application: switch, general purpose, audio, high voltage, super-beta, matched pair

XI. Physical packaging: through hole metal, through hole plastic, surface mount, ball grid array, power modules

XII. Amplification factor  $h_{fe}$  (transistor beta)

Thus, a particular transistor may be described as: silicon, surface mount, BJT, NPN, low power, high frequency switch.

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The bipolar junction transistor (BJT) was the first type of transistor to be mass-produced. Bipolar transistors are so named because they conduct by using both majority and minority carriers. The three terminals of the BJT are named emitter, base and collector. Two p-n junctions exist inside a BJT: the base/emitter junction and base/collector junction. “ The [BJT] is useful in amplifiers because the currents at the emitter and collector are controllable by the relatively small base current.” In an NPN transistor operating in the active region, the emitter-base junction is forward biased, and electrons are injected into the base region. Because the base is narrow, most of these electrons will diffuse into the reverse-biased base-collector junction and be swept into the collector; perhaps one-hundredth of the electrons will recombine in the base, which is the dominant mechanism in the base current. By controlling the number of electrons that can leave the base, the number of electrons entering the collector can be controlled.

Unlike the FET, the BJT is a low-input-impedance device. Also, as the base-emitter voltage ( $V_{be}$ ) is increased the base-emitter current and hence the collector-emitter current ( $I_{ce}$ ) increase exponentially according to the Shockley diode model and the Ebers-Moll model. Because of this exponential relationship, the BJT has a higher transconductance than the FET.

Bipolar transistors can be made to conduct by exposure to light, since absorption of photons in the base region generates a photocurrent that acts as a base current; the collector current is approximately beta times the photocurrent. Devices designed for this purpose have a transparent window in the package and are called phototransistors.

## **FIELD EFFECT TRANSISTORS**

The field-effect transistor (FET), sometimes called a unipolar transistor, uses either electrons (in N-channel FET) or holes (in P-channel FET) for conduction. The four terminals of the FET are named source, gate, drain, and body (substrate). On most FETs, the body is connected to the source inside the package, and this will be assumed for the following description.

In FETs, the drain-to-source current flows via a conducting channel that connects the source region to the drain region. The conductivity is varied by the electric field that is produced when a voltage is applied between the gate and source terminals; hence the current flowing between the drain and source is controlled by the voltage applied between the gate and source. As the gate-source voltage ( $V_{gs}$ ) is increased, the drain-source current ( $I_{ds}$ ) increases exponentially for  $V_{gs}$  below threshold, and then at a roughly quadratic rate ( $I_{ds} \propto (V_{gs} - V_T)^2$ ) (where  $V_T$  is the threshold voltage at which drain current begins) in the “space-charge-limited” region above threshold. A quadratic behavior is not observed in modern devices, for example, at the 65 nm technology node. For low noise at narrow bandwidth the higher input resistance of the FET is advantageous.

FETs are divided into two families: junction FET (JFET) and insulated gate FET (IGFET). The IGFET is more commonly known as metal-oxide-semiconductor FET (MOSFET), from their original construction as a layer of metal (the gate), a layer of oxide (the insulation), and a layer of semiconductor. Unlike IGFETs, the JFET gate forms a PN diode with the channel which lies between the source and drain. Functionally, this makes the N-channel JFET the solid state equivalent of the vacuum tube triode which, similarly, forms a diode between

its grid and cathode. Also, both devices operate in the depletion mode, they both have a high input impedance, and they both conduct current under the control of an input voltage.

Metal-semiconductor FETs (MESFETs) are JFETs in which the reverse biased PN junction is replaced by a metal-semiconductor Schottky-junction. These, and the HEMTs (high electron mobility transistors, or HFETs), in which a two-dimensional electron gas with very high carrier mobility is used for charge transport, are especially suitable for use at very high frequencies (microwave frequencies; several GHz).

Unlike bipolar transistors, FETs do not inherently amplify a photocurrent. Nevertheless, there are ways to use them, especially JFETs, as light-sensitive devices, by exploiting the photocurrents in channel-gate or channel-body junctions.

FETs are further divided into depletion-mode and enhancement-mode types, depending on whether the channel is turned on or off with zero gate-to-source voltage. For enhancement mode, the channel is off at zero bias, and a gate potential can “enhance” the conduction. For depletion mode, the channel is on at zero bias, and a gate potential (of the opposite polarity) can “deplete” the channel, reducing conduction. For either mode, a more positive gate voltage corresponds to a higher current for N-channel devices and a lower current for P-channel devices. Nearly all JFETs are depletion-mode as the diode junctions would forward bias and conduct if they were enhancement mode devices; most IGFETs are enhancement-mode types.[3]

## **OTHER TRANSISTORS TYPE**

### **I. Point-contact transistor, first type of transistor ever constructed**

### **II. Bipolar junction transistor (BJT)**

- a. Heterojunction bipolar transistor - up to 100s GHz, common in modern ultrafast and RF circuits
  - b. Grown-junction transistor, first type of BJT
  - c. Alloy-junction transistor, improvement of grown-junction transistor
    - i. Micro-alloy transistor (MAT), faster than alloy-junction transistor
    - ii. Micro-alloy diffused transistor (MADT), faster than MAT, type of a diffused-base transistor
    - iii. Post-alloy diffused transistor (PADT), faster than MAT, type of a diffused-base transistor
    - iv. Schottky transistor
    - v. Surface barrier transistor
  - d. Drift-field transistor
  - e. Avalanche transistor
  - f. Darlington transistors are two BJTs connected together to provide a high current gain equal to the product of the current gains of the two transistors.
  - g. Insulated gate bipolar transistors (IGBTs) use a medium power IGFET, similarly connected to a power BJT, to give a high input impedance. Power diodes are often connected between certain terminals depending on specific
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use. IGBTs are particularly suitable for heavy-duty industrial applications. The Asea Brown Boveri (ABB) 5SNA2400E170100 illustrates just how far power semiconductor technology has advanced. Intended for three-phase power supplies, this device houses three NPN IGBTs in a case measuring 38 by 140 by 190mm and weighing 1.5kg. Each IGBT is rated at 1,700 volts and can handle 2,400 amperes.

h. Photo transistor React to light

### **III. Field-effect transistor**

a. JFET, where the gate is insulated by a reverse-biased PN junction

b. MESFET, similar to JFET with a Schottky junction instead of PN one

i. High Electron Mobility Transistor (HEMT, HFET, MODFET)

c. MOSFET, where the gate is insulated by a thin layer of insulator

d. Inverted-T field effect transistor (ITFET)

e. FinFET The source/drain region forms fins on the silicon surface.

f. FREDFET Fast-Reverse Epitaxial Diode Field-Effect Transistor

g. Thin film transistor Used in LCD display.

h. OFET Organic Field-Effect Transistor, in which the semiconductor is an organic compound

i. Ballistic transistor

j. Floating-gate transistor Used for non-volatile storage.

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k. FETs used to sense environment

i. Ion sensitive field effect transistor To measure ion concentrations in solution.

ii. EOSFET Electrolyte-Oxide-Semiconductor Field Effect Transistor (Neurochip)

iii. DNAFET Deoxyribonucleic acid field-effect transistor

#### **IV. Spacistor**

**V. Diffusion transistor, formed by diffusing dopants into semiconductor substrate; can be both BJT and FET**

**VI. Unijunction transistors can be used as simple pulse generators.**

They comprise a main body of either P-type or N-type semiconductor with ohmic contacts at each end (terminals Base1 and Base2). A junction with the opposite semiconductor type is formed at a point along the length of the body for the third terminal (Emitter).

VII. Single-electron transistors (SET) consist of a gate island between two tunnelling junctions. The tunnelling current is controlled by a voltage applied to the gate through a capacitor.

VIII. Spin transistor Magnetically-sensitive

IX. Nanofluidic transistor Control the movement of ions through sub-microscopic, water-filled channels. Nanofluidic transistor, the basis of future chemical processors

#### **X. Multigate devices**

a. Tetrode transistor

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b. Pentode transistor

c. Multigate device

d. Trigate transistors (Prototype by Intel)

e. Dual gate FETs have a single channel with two gates in cascode; a configuration that is optimized for high frequency amplifiers, mixers, and oscillators

f. Semiconductor material

### **XI. The first BJTs were made from germanium (Ge).**

Silicon (Si) types currently predominate but certain advanced microwave and high performance versions now employ the compound semiconductor material gallium arsenide (GaAs) and the semiconductor alloy silicon germanium (SiGe). Single element semiconductor material (Ge and Si) is described as elemental.

Rough parameters for the most common semiconductor materials used to make transistors are given in the table below; it must be noted that these parameters will vary with increase in temperature, electric field, impurity level, strain and various other factors:

### **Semiconductor material characteristics**

Semiconductor

material

Junction forward

voltage

V @ 25 °C

Electron mobility

m<sup>2</sup>/(V·s) @ 25 °C

Hole mobility

m<sup>2</sup>/(V·s) @ 25 °C

Max. junction temp.

°C

Ge

0.27

0.39

0.19

70 to 100

Si

0.71

0.14

0.05

150 to 200



GaAs

1. 03

0. 85

0. 05

150 to 200

Al-Si junction

0. 3

—

—

150 to 200

The junction forward voltage is the voltage applied to the emitter-base junction of a BJT in order to make the base conduct a specified current. The current increases exponentially as the junction forward voltage is increased. The values given in the table are typical for a current of 1 mA (the same values apply to semiconductor diodes). The lower the junction forward voltage the better, as this means that less power is required to “drive” the transistor. The junction forward voltage for a given current decreases with increase in temperature. For a typical silicon junction the change is approximately  $-2.1 \text{ mV}/^\circ\text{C}$ .

The density of mobile carriers in the channel of a MOSFET is a function of the electric field forming the channel and of various other phenomena such as the impurity level in the channel. Some impurities, called dopants, are introduced deliberately in making a MOSFET, to control the MOSFET electrical behavior.

The electron mobility and hole mobility columns show the average speed that electrons and holes diffuse through the semiconductor material with an electric field of 1 volt per meter applied across the material. In general, the higher the electron mobility the faster the transistor. The table indicates that Ge is a better material than Si in this respect. However, Ge has four major shortcomings compared to silicon and gallium arsenide:

- I. its maximum temperature is limited
- II. it has relatively high leakage current
- III. it cannot withstand high voltages
- IV. it is less suitable for fabricating integrated circuits

Because the electron mobility is higher than the hole mobility for all semiconductor materials, a given bipolar NPN transistor tends to be faster than an equivalent PNP transistor type. GaAs has the highest electron mobility of the three semiconductors. It is for this reason that GaAs is used in high frequency applications. A relatively recent FET development, the high electron mobility transistor (HEMT), has a heterostructure (junction between different semiconductor materials) of aluminium gallium arsenide (AlGaAs)-gallium arsenide (GaAs) which has double the electron mobility of a GaAs-

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metal barrier junction. Because of their high speed and low noise, HEMTs are used in satellite receivers working at frequencies around 12GHz.

Max. junction temperature values represent a cross section taken from various manufacturers' data sheets. This temperature should not be exceeded or the transistor may be damaged.

Al-Si junction refers to the high-speed (aluminum-silicon) semiconductor-metal barrier diode, commonly known as a Schottky diode. This is included in the table because some silicon power IGFETs have a parasitic reverse Schottky diode formed between the source and drain as part of the fabrication process. This diode can be a nuisance, but sometimes it is used in the circuit.[4]

## **Packaging**

### **Through-hole transistors (tape measure marked in centimetres)**

Transistors come in many different packages (chip carriers) (see images). The two main categories are through-hole (or leaded), and surface-mount, also known as surface mount device (SMD). The ball grid array (BGA) is the latest surface mount package (currently only for large transistor arrays). It has solder “balls” on the underside in place of leads. Because they are smaller and have shorter interconnections, SMDs have better high frequency characteristics but lower power rating.

Transistor packages are made of glass, metal, ceramic or plastic. The package often dictates the power rating and frequency characteristics.

Power transistors have large packages that can be clamped to heat sinks for enhanced cooling. Additionally, most power transistors have the collector or

drain physically connected to the metal can/metal plate. At the other extreme, some surface-mount microwave transistors are as small as grains of sand.

Often a given transistor type is available in different packages. Transistor packages are mainly standardized, but the assignment of a transistor's functions to the terminals is not: different transistor types can assign different functions to the package's terminals. Even for the same transistor type the terminal assignment can vary (normally indicated by a suffix letter to the part number- i. e. BC212L and BC212K)[5].

## **CONCLUSION**

A unified noise model which incorporates both the number fluctuation and the correlated surface mobility fluctuation mechanism is discussed. The latter is attributed to the Coulombic scattering effect of the fluctuating oxide charge. The model has a functional form resembling that of the number fluctuation theory, but at certain bias conditions it may reduce to a form compatible with Hooge's empirical expression. The model can unify the noise data reported in the literature, without making any ad hoc assumption on the noise generation mechanism. Specifically, the model can predict the right magnitude and bias dependence of the empirical Hooge parameter.

Simulated noise characteristics obtained with a circuit-simulation-oriented noise model based on the new formulation were compared with experimental noise data. Excellent agreement between the calculations and measurement was observed in both the linear and saturation regions for MOS transistors fabricated by different technologies. The work shows that the flicker noise in MOS transistors can be completely explained by the trap

charge fluctuation mechanism, which produces mobile carrier number fluctuation and correlated surface mobility fluctuation. In electronics, a transistor is a semiconductor device commonly used to amplify or switch electronic signals. A transistor is made of a solid piece of a semiconductor material, with at least three terminals for connection to an external circuit. A voltage or current applied to one pair of the transistor's terminals changes the current flowing through another pair of terminals. Because the controlled (output) power can be much larger than the controlling (input) power, the transistor provides amplification of a signal. The transistor is the fundamental building block of modern electronic devices, and is used in radio, telephone, computer and other electronic systems. Some transistors are packaged individually but most are found in integrated circuits.

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