FRONT COVER

# THE EFFECT OF PHOSPHOROUS IMPLANT IN CONVERTING THE ENHANCEMENT MODE TRANSISTOR INTO DEPLETION MODE TRANSISTOR

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# The Effect of Phosphorous Implant In Converting The Enhancement Mode Transistor Into Depletion Mode Transistor

by

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**Abstrak**

Transistor kesan medan separuh pengalir oksida logam (MOSFET) adalah bahan yang asas dalam aplikasi elektronik. Dalam kebanyakan litar sifat MOSFET yang membekalkan arus pada Vg=0 V. Transistor jenis ini sentiasa dalam keadaan 'on' melainkan polarity terbalik Vg dikenakan padanya. Dalam kajian ini, pelbagai ujikaji yang menyeluruh dijalankan ke atas proses parameter yang mempengaruhi transistor mod susutan. Kajian ini lebih menekankan kepada penanaman ion untuk membentuk saluran susutan. Setiap langkah proses ini dalam menghasilkan suatu susutan jenis MOSFET yang berjaya amat penting sekali. Untuk menyokong kajian ini, Rekacipta Eksperimen (DOE) untuk 'penanaman ion dose dan tenaga ' telah dilaksanakan di kemudahan pembuatan, MIMOS. Proses teknologi 0.5um CMOS telah digunakan sebagai garis asas dalam menghasilkan n-type susutan mode MOSFET. Selain daripada menjalankan eksperimen, perisian simulasi (ATHENA dan ATLAS ) juga digunakan dalam kajian ini. Ini adalah untuk mengurangkan kos dan masa dalam menghasilkan wafer experiment. Perbezaan antara hasil kajian ujian eksperimen dan keluaran simulasi juga dibincangkan secara mendalam dalam tesis ini. Selain daripada itu, masalah dan pemerhatian dari eksperimen ini juga diberi perhatian dan dibincangkan. Isu yang paling utama ialah titik dua puncak pada lengkung transconductance. Berdasarkan hasil eksperimen, didapati bahawa ion fosforus dengan dos *3.3e12 cm-2* dan tenaga *60 keV* yang digunakan dalam saluran susutan penanaman ion telah menghasilkan MOSFET mod susutan dengan ciri-ciri yang bagus dengan voltan ambang sebanyak *-0.7 V*.

**Abstract**

Metal-Oxide-Semiconductor field effect transistor (MOSFET) forms the basis in most of electronic applications. In certain part of electronic circuitry, there is a requirement to use depletion mode of MOSFET which delivers current at $V_g$=0V. This type of transistor is normally on unless reverse-polarity $V_g$ is applied to turn it off. In this research, thorough investigations on process parameters that affect the performance of depletion mode transistor have been studied. The study was emphasized on the ion implantation to forms the depletion channel. It is a very crucial process step in creating a successful depletion type MOSFET. To support the study, Design of Experiment (DOE) for ion implantation dose and energy has been implemented in MIMOS fabrication facility. The 0.5um CMOS process technology was used as a baseline to produce n-type depletion mode MOSFET. Besides running the experiment, simulation software (ATHENA and ATLAS) were used in this study to reduce the cost and time of producing experiment wafers. Comparison of experiment test results and simulation output was also discussed in details in this thesis. On the other hand, problems and observations from the experiment were highlighted and discussed too. One of the main issues is on the two-peak point of transconductance curve. According to the experimental results, it can found that *phosphorus* ion with dose *3.3e12* $cm^{-2}$ and energy *60* keV used in depletion channel implant should produce good characteristics of depletion mode MOSFET with threshold voltage

*-0.7* V.

i. Introduction

# CHAPTER 1

# INTRODUCTION

## 1.0 Introduction

A transistor is a semiconductor device, commonly used as an amplifier or an electrically controlled switch. The transistor is the fundamental building block of the circuitry in computers, cellular phones, and all other modern electronic devices. Because of its fast response and accuracy, the transistor is used in a wide variety of digital and analog functions, including amplification, switching, voltage regulation, signal modulation, and oscillators. Transistors may be packaged individually or as part of an integrated circuit, some with over a billion transistors in a very small area. An electrical signal can be amplified by using a device that allows a small current or voltage to control the flow of a much larger current. Transistors are the basic devices providing control of this kind. Modern transistors are divided into two main categories: bipolar junction transistors (BJTs) and field effect transistors (FETs). Application of current in BJTs and voltage in FETs between the input and common terminals increases the conductivity between the common and output terminals, thereby controlling current flow between them. The transistor characteristics depend on their type[ Wikipedia, 2007].

The term "transistor" originally referred to the point contact type, which saw very limited commercial application, being replaced by the much more practical bipolar junction types in the early 1950s. Today's most widely used schematic symbol, like the term "transistor", originally referred to these long-obsolete devices. For a short time in the early 1960s, some manufacturers and publishers of electronics magazines started to replace these with symbols that more accurately depicted the different construction of the bipolar transistor, but this idea was soon abandoned. In analog circuits, transistors are used in amplifiers, (direct current amplifiers, audio amplifiers, radio frequency amplifiers), and linear regulated power supplies[Wikipedia, 2007].

Transistors are also used in digital circuits where they function as electronic switches, but rarely as discrete devices, almost always being incorporated in monolithic Integrated Circuits. Digital circuits include logic gates, random access memory (RAM), microprocessors, and digital signal processors (DSPs). The transistor is considered by many to be the greatest invention of the twentieth century. 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 vanishingly low per-transistor costs. Although billions of individual (known as *discrete*) transistors are still used, the vast majority produced are in integrated circuits (often abbreviated as *IC* and also called *microchips* or simply *chips*) along with diodes, resistors, capacitors and other electronic components to produce complete electronic circuits [Wikipedia, 2007].

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). The transistor's low cost, flexibility and reliability have made it a universal device for non-mechanical tasks, such as digital computing. Transistorized circuits have replaced electromechanical devices for the control of appliances and machinery as well. 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. Because of the low cost of transistors and hence digital computers, there is a trend to digitize information. With digital computers offering the ability to quickly find, sort and process digital information, more and more effort has been put into making information digital. As a result, today, much media data is delivered in digital form, finally being converted and presented in analog form to the user. Areas influenced by the Digital Revolution include television, radio, and newspapers [Wikipedia, 2007].

Transistors are categorized by:

- Semiconductor material : germanium, silicon, gallium arsenide, silicon carbide, etc.
- Structure: BJT, JFET, IGFET (MOSFET), IGBT, "other types"
- Polarity: NPN, PNP (BJTs); N-channel, P-channel (FETs)
- Maximum power rating: low, medium, high
- 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).

Application: switch, general purpose, audio, high voltage, super-beta, matched pair. Physical packaging: through hole metal, through hole plastic, surface mount, ball grid array, power modules Thus, a particular transistor may be described as: *silicon, surface mount, BJT, NPN, low power, high frequency switch.*

In electronics, a **transistor** is a semiconductor device commonly used to amplify or switch electronic signals. The transistor is the fundamental building block of computers, and all other modern electronic devices. Some transistors are packaged individually but most are found in integrated circuits [Wikipedia, 2007].


Assorted discrete transistor [Wikipedia, 2007]

Transistor has 2 mode of operations i.e enhancement mode and depletion mode.

There are two types of MOSFETs, which differ in construction and in operation. One type is called a depletion-mode MOSFET and the other  called enhancement mode. A depletion-mode MOSFET conducts current without a gate bias. In a n-channel device, a thin n-type region exists under the oxide in the absence of an applied bias. It connects the source and drain allowing current to flow. In fact, a negative voltage is required to drive the electrons out of (deplete) the region to increase channel resistance and reduce current flow [Wikipedia, 2007].

## 1.1 Comparison Enhancement and Depletion Mode Transistor

In the early days of transistor circuit design, the bipolar junction transistor, or BJT, was the most commonly used transistor. Even after MOSFETs became available, the BJT remained the transistor of choice for digital and analog circuits because of their ease of manufacture and speed. However, desirable properties of MOSFETs, such as their utility in low-power devices, have made them the ubiquitous choice for use in digital circuits and a very common choice for use in analog circuits. BJT used as an electronic switch, in grounded-emitter configuration [Paul Gilliard, 2007].

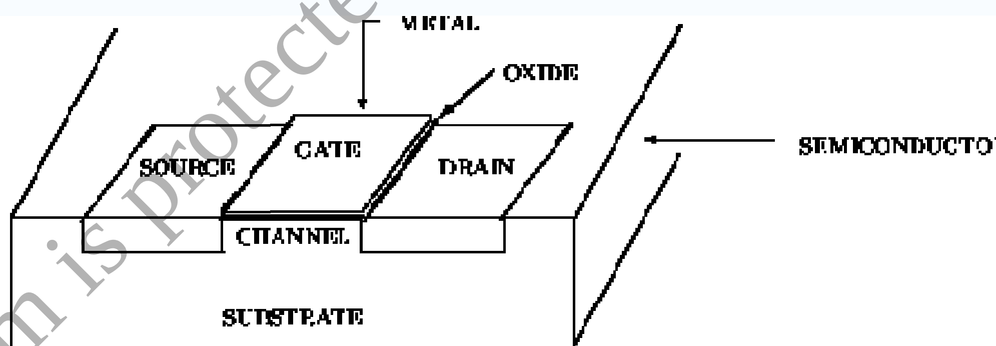



**Figure 1: Basic transistor cross section**

The most basic element in the design of a large scale integrated circuit is the transistor. For the processes that we will discuss, the type of transistor available is the Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET). These transistors are formed as a ``sandwich" consisting of a semiconductor layer, usually a slice, or wafer, from a single crystal of silicon; a layer of silicon dioxide (the oxide) and a layer of metal [Paul Gilliard, 2007].

These layers are patterned in a manner which permits transistors to be formed in the semiconductor material (the ``substrate"); a diagram showing a typical (idealized) MOSFET is shown in Figure 1. Silicon dioxide is a very good insulator, so a very thin layer, typically only a few hundred molecules thick, is required. Actually, the transistors which we will use do not use metal for their gate regions, but instead use polycrystalline silicon (poly). Polysilicon gate FET's have replaced virtually all of the older devices using metal gates in large scale integrated circuits. (Both metal and polysilicon FET's are sometimes referred to as IGFET's --- insulated gate field effect transistors, since the silicon dioxide under the gate is an insulator [Paul Gilliard, 2007].

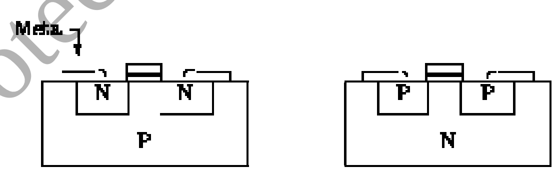



**Figure 2: NPN and PNP Transistor**

The source and drain regions are quite similar, and are labeled depending on what they are connected. Refer to figure 2. The source is the terminal, or node, which acts as the source of charge carriers; charge carriers leave the source and travel to the drain. In the case of a N channel MOSFET, the source is the more negative of the terminals; in the case of a P channel device, it is the more positive of the terminals. The area under the gate oxide is called the ``channel". The MOSFET can operate as a very efficient switch for current flowing between the source and drain region of the device. For the simplest type of MOSFET, the ``enhancement mode MOSFET'', which acts as a ``normally open'' switch [Paul Gilliard, 2007].

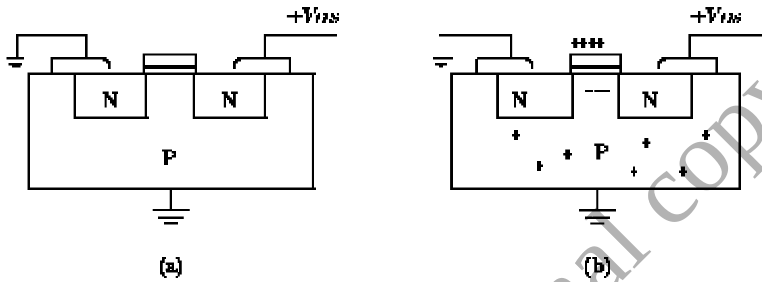



**Figure 3 (a) N-channel Mosfet and (b) N-channel Mosfet in operation**

Figure 3 (a) shows a N-channel MOSFET with the source and drain connected to power (VDS) and ground (VSS); the substrate, or body of the device, is also connected to ground. In this case, there is a reverse biased PN junction between at least one of the N wells and the substrate, so no current can flow through the substrate. In particular, there will be no current flow in the channel region under the gate of the transistor, and therefore no current will flow between the source and drain of the device. Under these conditions, the MOSFET is turned *off [*Paul Gilliard, 2007].

Figure 3 (b) shows the same N-channel MOSFET with a positive charge applied to the gate of the device. Under these circumstances, if the gate is given a sufficiently large charge, negative charge carriers (electrons) will be attracted from the bulk of the substrate material into the channel region immediately below the oxide under the gate. When more electrons are attracted into this region than there are positive charge carriers (holes) in the channel, then the channel effectively behaves as an N type region, and current can flow between the source and the drain. When this happen, the MOSFET is turned *on*. Note that a certain minimum charge must be applied to the gate to overcome the excess of holes already in the channel region because of the P type doping in the substrate.

This means that the switch is not turned on immediately; rather there must be some minimum amount of charge applied to the gate before the transistor is switched on.
The voltage which must be applied to the gate before the transistor allow current to flow between the source and drain is called the ``threshold voltage'', designated as Vth.
This type of transistor is called a N channel enhancement mode MOSFET. (It is called N channel because the conduction in the channel is due to N type charge carriers; it is said to be an ``enhancement mode'' device because the channel conduction is enhanced by a charge applied to the gate.) Figure 4 shows a set of typical characteristic curves for the current *IDS* between the drain and source of a MOSFET as a function of the voltage *VDS* for a range of gate voltages *VGS* [Paul Gilliard, 2007].

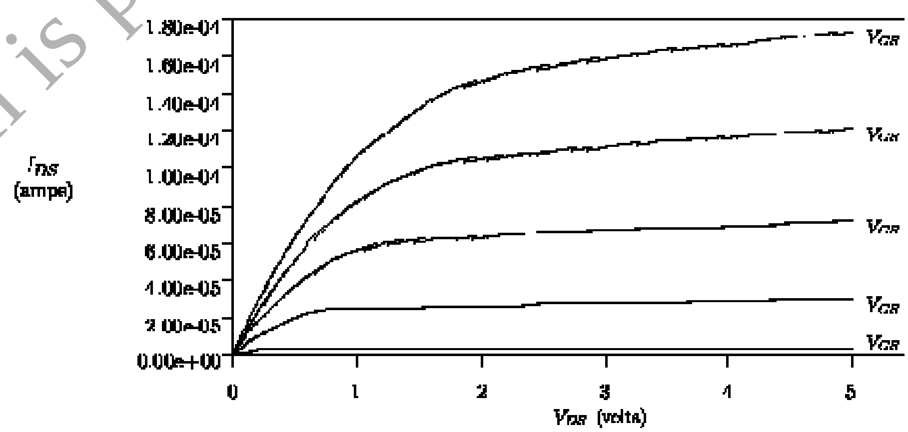



**Figure 4**

A second type of MOSFET can also be constructed; this type of device is commonly used in purely NMOS designs, but is not used in CMOS designs. (Presently, we only have access to CMOS processes.) This type of MOSFET, the ``depletion mode MOSFET'', acts as a ``normally closed'' switch. Its behavior can qualitatively be explained with reference on Figure 5 which shows a N channel depletion mode MOSFET [Paul Gilliard, 2007].

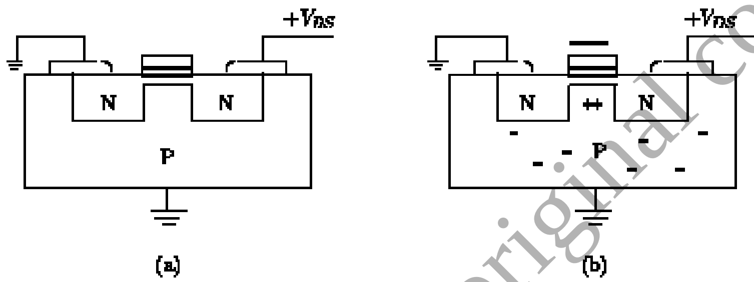



**Figure 5: N-channel depletion mode Mosfet**

In the depletion mode MOSFET, a thin layer of semiconductor material immediately beneath the gate oxide is permanently doped with the same type material as the source and drain regions (but different from the bulk of the substrate semiconductor material). This thin layer allows conduction to occur in the channel region when no charge is applied to the gate. If a negative charge is applied to the gate, then the negative charge carriers in the thin N-doped region immediately beneath the gate oxide will be repelled from this region, leaving no free charge carriers, and conduction will cease. In the depletion mode MOSFET, a charge (with the same polarity as the drain dopant) applied to the gate turns the transistor *off*. Depletion mode MOSFETs find their most common use not as switches but as resistors. As a permanently ``on'' transistor, the device has a high resistance compared with the doped semiconductor material itself, and the resistance is readily variable by modifying the size of the transistor. (At fabrication time, the resistance can be modified by varying the number of ions which are implanted in the gate region of the device) [Paul Gilliard, 2007].

The commonly used circuit symbols for N- and P- channel enhancement and depletion mode MOSFETs are shown in figure 6 (a) and (b).

Figure 6 (a) shows the commonly used circuit symbols for P- and N- channel enhancement mode MOSFETs; the corresponding circuit symbols for depletion mode devices are shown in Figure 6 (b).

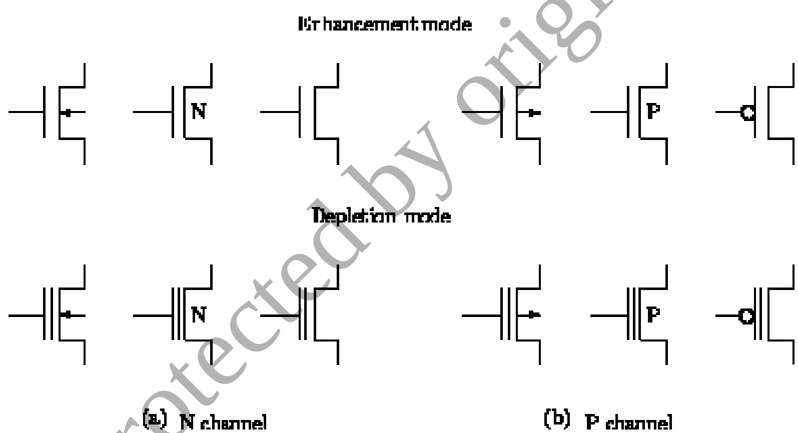
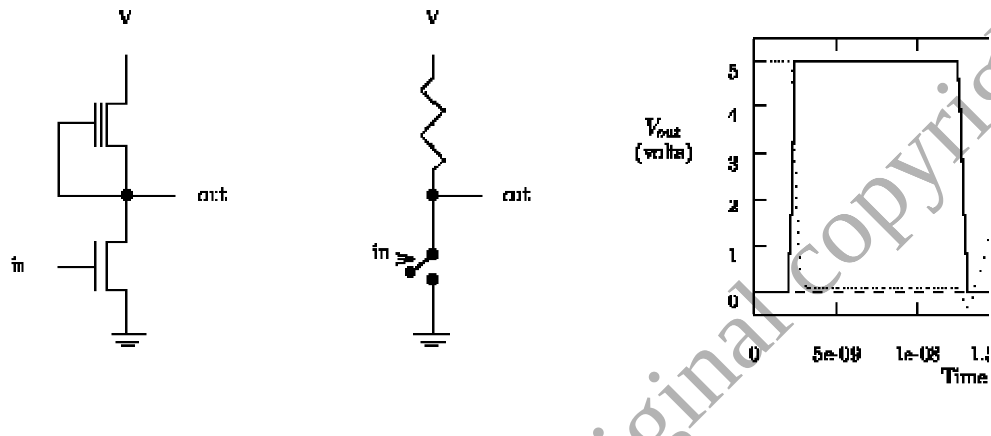



**Figure 6**

Both enhancement and depletion mode transistors are used in many of today's microelectronic circuits. The most popular circuit technology using both enhancement and depletion mode devices is the conventional NMOS technology. In this technology, depletion mode transistors are mainly as resistors, and enhancement mode transistors are used as switches. Figure 7 shows a typical inverter implemented in this technology, together with its switch equivalent. Also shown is a plot of the output of a typical example of such an inverter for a given input pulse. (The input pulse has a rise and fall time of 0.5 ns.) [Paul Gilliard, 2007].



(a) (b) (c)

**Figure 7**

The gate of the depletion mode transistor is connected to its drain, to keep the transistor permanently turned on. The depletion mode transistor is used as a ``pull-up'' resistor, and the enhancement mode transistor is used as a switch to ``pull down'' the output when the switch is turned on. Note that in this technology, the resistance of the permanently turned on depletion mode transistor must be large compared with the ``on'' resistance of the enhancement mode transistor, but small compared with the ``off'' resistance of the transistor. This type of logic is often called a ``ratioed logic'', since the ratio of the pull-up resistance to the pull-down resistance effectively determines the voltage in which the output of the device changes state [Paul Gilliard, 2007].

The large resistive pull-up transistor causes three particular problems with this technology:

1. The depletion mode transistor must be made large ( *i.e.*, long and thin) to create the large ``on'' resistance.
2. When driving a capacitive output load such as the gate of another transistor, the charging time (proportional to *RdepC*) will be long compared to the discharging time (proportional to *RenhC*. This effect is clearly evident in Figure 7 (c).
3. The device consumes DC power whenever the enhancement mode pull down device is turned on, due to the resistive losses in the pull-up transistor.

The third problem becomes more serious as feature sizes for transistors decrease, because the number of such resistors per unit area increases, and the devices may not dissipate the heat as well, resulting in device failure due to overheating [Paul Gilliard, 2007].

### 1.1.1 Transistor Application;

**i) Switches**

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 [Wikipedia, 2007].

**ii) T Amplifiers**

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. Transistors are commonly used in modern musical instrument amplifiers, in which circuits up to a few hundred watts are common and relatively cheap. Transistors have largely replaced valves (electron tubes) in instrument amplifiers. Some musical instrument amplifier manufacturers mix transistors and vacuum tubes in the same circuit, to utilize the inherent benefits of both devices [Wikipedia, 2007].

**iii) Computers**

The "first generation" of electronic computers used vacuum tubes, which generated large amounts of heat, were bulky, and were unreliable. The development of the transistor was key to computer miniaturization and reliability. The "second generation" of computers, through the late 1950s and 1960s featured boards filled with individual transistors and magnetic memory cores. Subsequently, transistors, other components, and their necessary wiring were integrated into a single, mass-manufactured component: the integrated circuit [Wikipedia, 2007].