TO IMPROVE THE PERFORMANCE OF MOSFET

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Table of Content

CERTIFICATE

This is to certify that project report entitled" **TO IMPROVE THE PERFORMANCE OF MOSFET**", submitted by **Palak Gaba** (**111062**), **Ankit Agarwal** (**111069**), **Aashna Jain** (**111095**) in partial fulfilment for the award of degree of Bachelor of Technology in Electronics and Communication Engineering to Jaypee University of Information Technology, Waknaghat, Solan has been carried out under my supervision.

This work has not been submitted partially or fully to any other University or Institute for the award of this or any other degree or diploma.

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ABSTRACT

A Metal Oxide Semiconductor Field Effect Transistor is a transistor used for amplifying or switching electronic signals. The body of a MOSFET is usually connected to the source terminal which makes it a three-terminal device similar to other Field Effect Transistors (FET).

The MOSFET (metal oxide semiconductor field-effect transistor) is by far the most common semiconductor device, and the primary building block in all commercial processors, memories, and digital integrated circuits. Since the first microprocessors were introduced approximately 40 years ago this device has experienced tremendous development, and today it is being manufactured with feature sizes of 22 nm and smaller.

The MOS Field Effect Transistor is also the fundamental building block of MOS and CMOS digital integrated circuits. Compared to the bipolar junction transistor (BJT), the MOS transistor occupies a relatively smaller silicon area, and its fabrication involves fewer processing steps.

The NMOS transistor is used as the primary switching device in virtually all digital circuit applications, whereas the PMOS transistor is used mostly in conjunction with the NMOS device in CMOS circuits.

In this project, we compare the performance of conventional MOSFET using different semiconductor materials on the basis of various parameters and curves.

The materials used are Silicon (Si), Germanium (Ge), Gallium Arsenide (GaAs), Gallium Nitride (GaN) and Graphene.

An extensive research is done on Graphene where we studied the structure, properties, advantages and disadvantages of the material in depth. Graphene's properties are compared with properties of Silicon, Germanium, Gallium Arsenide and Gallium Nitride proving that Graphene is the future of the Electronics industry and is already replacing other material in a number of applications.

_____   _____

Signature of Student(s)   Signature of Supervisor

Name: Palak Gaba, Ankit Agarwal, Aashna Jain   Name: Asst. Prof. Akhil Ranjan

Date: 25/05/2015   Date: 25/05/2015

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ACRONYMS

Symbol/Acronym	Explanation
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
FET	Field Effect Transistor
JFET	Junction Field Effect Transistor
NMOS	Negative Channel Metal Oxide Semiconductor Field Effect Transistor
PMOS	Positive Channel Metal Oxide Semiconductor Field Effect Transistor
Si	Silicon
Ge	Germanium
GaAs	Gallium Arsenide
GaN	Gallium Nitride
μ	Mobility
μ_N	Mobility of electron
μ_P	Mobility of proton
Ni	Intrinsic concentration of carriers
CMOS	Complementary Metal Oxide Semiconductor Field Effect Transistor
BJT	Bipolar Junction Transistor
S	Source
G	Gate
D	Drain
B	Body
W	Width
L	Length
DC	Direct Current
AC	Alternate Current
IC	Integrated Circuit
SCE	Short Channel Effects
NEMS	Nano ElectroMechanical Systems
DNA	Deoxyribo Nucleic Acid
MoS2	Molybdenite
OLED	Organic Light Emitting Diode
SiO_2	Silicon Oxide
InP	Indium Phosphide
InAs	Indium Arsenide
InSb	Indium Antimonide
CAD	Computer Aided Design
ITO	Indium Tin Oxide
Λ	Fitting parameter
Id	Drain Current
Vg/Vgs	Gate Voltage
Vd/Vds	Drain Voltage
V_{SB}	Substrate Voltage
G_m	Trans-conductance
g_0/g_d	Output Conductance

ϕ_{GC}	Gate Electrode Potential
ϕ_F	Fermi Potential
ϕ_M	Work Potential of Metal
ϕ_S	Work Potential of Substrate
V_{FB}	Flat-band Voltage
C_{OX}	Oxide Capacitance
Q_B	Depletion Region Charge Density at Surface Inversion
ε_0	Absolute Permittivity
ε	Relative Permittivity of the material
KT/q	Thermal Voltage
N_A	Acceptor Concentration
N_D	Donor Concentration
Q_{OX}	Charge at oxide layer
V_T	Threshold Voltage
V_c	Channel Voltage
V_s	Source Voltage
R_T	Recombination rate
$\tau h0$	Lifetime of Holes
$\tau e0$	Lifetime of Electrons
$E(k)$	Energy Dispersion
v_F	Velocity of electrons
eV	Electron Volt

1) OBJECTIVE

1.1) WHY MOSFET?

MOSFET is the most common semiconductor device, and the primary building block in all commercial processors, memories, and digital integrated circuits. It is essentially a miniaturized switch.

MOSFET has advantages over the conventional junction FET, or JFET because the gate is insulated electrically from the channel, no current flows between the gate and the channel, no matter what the gate voltage (as long as it does not become so great that it causes physical breakdown of the metallic oxide layer).

MOSFET has practically infinite impedance and is well suited to high-speed switching applications.

1.2) WORK DONE

We have simulated the Conventional MOSFET with different semiconductor materials (Si, Ge, GaAs, GaN). The input, drain characteristics (Id vs Vg and Id vs Vd) and the small signals parameters (gm and g0) of all the MOSFETs are compared. Extensive study on the Graphene has been undertaken to understand the scope of developing a transistor whose substrate would be only Graphene.

The ultimate aim is:

- To reduce the current ratings.

- To decrease the threshold voltage.

- To improve trans-conductance and output conductance.

2) TECHNICAL DETAILS

2.1) ABOUT MOSFET

2.1.1) WHAT IS MOSFET

The metal–oxide–semiconductor field-effect transistor (MOSFET, MOS-FET, or MOS FET) is a type of transistor used for amplifying or switching electronic signals.

Although the MOSFET is a four-terminal device with source (S), gate (G), drain (D), and body (B) terminals, the body (or substrate) of the MOSFET is often connected to the source terminal, making it a three-terminal device like other field-effect transistors. Because these two terminals are normally connected to each other (short-circuited) internally, only three terminals appear in electrical diagrams.

It is a special type of FET that works by electronically varying the width of a channel along which charge carriers (electrons or holes) flow. The wider the channel, the better the device conducts. The charge carriers enter the channel at the source, and exit via the drain. The width of the channel is controlled by the voltage on an electrode called the gate, which is located physically between the source and the drain and is insulated from the channel by an extremely thin layer of oxide.

2.1.2) WORKING AND CONSTRUCTION OF MOSFET

The MOSFET is essentially a miniaturized switch. The source and drain contacts (the input and output of the switch) are both Ohmic (low resistance) contacts to heavily doped n-type regions of the device. Between these two contacts is a region of p-type semiconductor. The gate contact lies above the p-type semiconductor, slightly overlapping the two n-type regions. It is separated from the semiconductor by a thin layer of Silicon oxide, so that it forms a capacitor with the underlying semiconductor. Applying a voltage to the gate changes the local band structure beneath it through the Field Effect. A sufficiently high voltage can cause the semiconductor to change from p-type to n-type in a thin layer (the channel) underneath the gate. This is known as inversion and the channel is sometimes referred to as the inversion layer. The channel connects the two n-type regions of semiconductor with a thin n-type region under the gate. This region has a significantly lower resistance than the series resistance of the np/pn junctions that separated the source and the gate before the gate voltage produced the inversion layer. Consequently applying a gate voltage can be used to change the resistance of the device from a high to a low value. The gate voltage where a significant current begins to flow is called the threshold or turn-on voltage.

As the voltage between the drain and the source is increased the current carried by the channel eventually saturates through a process known as pinch-off, in which the channel narrows at one end due to the effect of the field parallel to the surface. The channel width is controlled by the gate voltage. Typically a larger gate voltage results in wider channel and consequently a lower resistance for a given drain voltage. Additionally the saturation current is larger for a higher gate voltage.
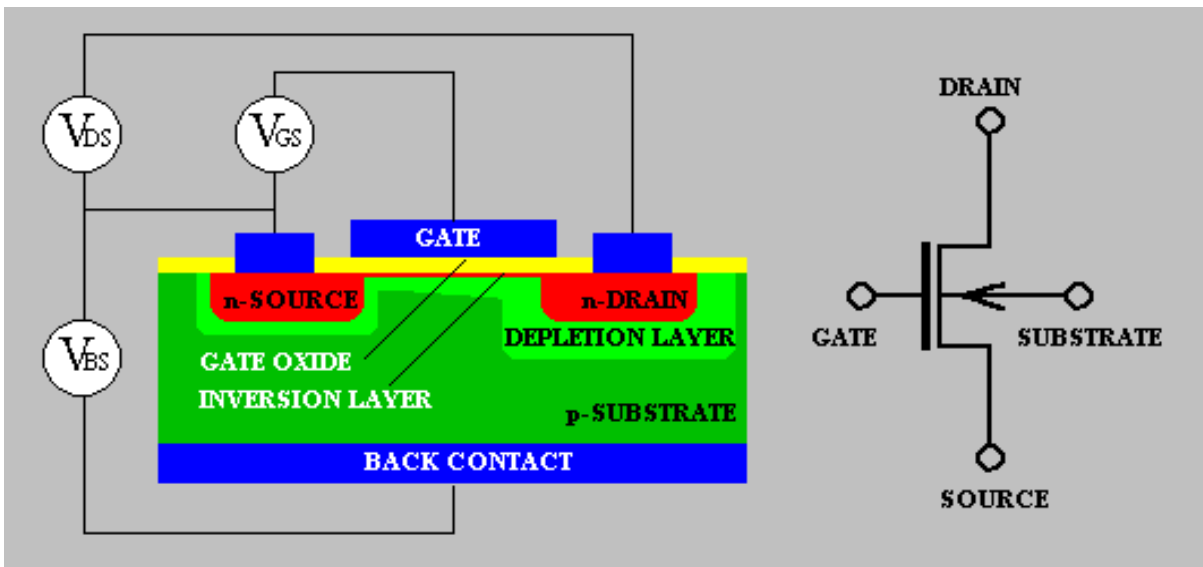

Figure 1: The current flows from the source to the gate through a channel underneath the gate. The size of the channel is controlled by the gate voltage.

2.1.3) CALCULATION OF THRESHOLD VOLTAGE

For all practical purposes, we can identify four physical components of the threshold voltage: (i) the work function difference between the gate and the channel, (ii) the gate voltage component to change the surface potential, (iii) the gate voltage component to offset the depletion region charge, and (iv) the voltage component to offset the fixed charges in the gate oxide and in the silicon-oxide interface.

The work function difference ϕ_{GC} between the gate and the channel reflects the built-in potential of the MOS system, which consists of the p-type substrate, the thin silicon dioxide layer, and the gate electrode. Depending on the gate material, the work function difference is

$$\Phi_{GC} = \phi_F(substrate) - \phi_M \qquad \text{for metal gate}$$

(2.4.1)

$$\Phi_{GC} = \phi_F(substrate) - \phi_F(gate) \qquad \text{for polysilicon gate} \qquad (2.4.2)$$

where,

$$\phi_F(substrate) = \frac{kT}{q} \ln\left(\frac{n_i}{N_A}\right) \tag{2.4.3}$$

The first component of the threshold voltage accounts for part of the voltage drop across the MOS system that is built-in. Now, the externally applied gate voltage must be changed to achieve surface inversion, i.e., to change the surface potential by - $2\phi_F$. This will be the second component of the threshold voltage.

Another component of the applied gate voltage is necessary to offset the depletion region charge, which is due to the fixed acceptor ions located in the depletion region near the surface. We can calculate the depletion region charge density at surface inversion ($\phi_S = -\phi_F$)

$$Q_{B0} = -\sqrt{2q \cdot N_A \cdot \varepsilon_{Si} \cdot \left|-2\phi_F\right|} \tag{2.4.4}$$

Note that if the substrate (body) is biased at a different voltage level than the source, which is at ground potential (reference), then the depletion region charge density can be expressed as a function of the source-to-substrate voltage V_{SB}.

$$Q_B = -\sqrt{2q \cdot N_A \cdot \varepsilon_{Si} \cdot \left|-2\phi_F + V_{SB}\right|} \tag{2.4.5}$$

The influence of a non-ideal physical phenomenon is considered. There always exists a fixed positive charge density Q_{ox} at the interface between the gate oxide and the silicon substrate, due to impurities and/or lattice imperfections at the interface. The gate voltage component that is necessary to offset this positive charge at the interface is - Q_{ox}/C_{ox}. Now, we can combine all of these voltage components to find the threshold voltage.

$$V_T = \Phi_{GC} - 2\phi_F - \frac{Q_B}{C_{ox}} - \frac{Q_{ox}}{C_{ox}} \tag{2.4.6}$$

The threshold voltage expression given in (2.4.6) can be used both for n-channel and p-channel MOS transistors.

Specifically,

- The substrate Fermi potential ϕ_F is negative in NMOS, positive in PMOS.
- The depletion region charge densities Q_{B0} and Q_B are negative in NMOS, positive in PMOS.

4

- The substrate bias voltage V_{SB} is positive in NMOS, negative in PMOS.

Typically, the threshold voltage of an enhancement-type n-channel MOSFET is a positive quantity, whereas the threshold voltage of a p-channel MOSFET is negative.

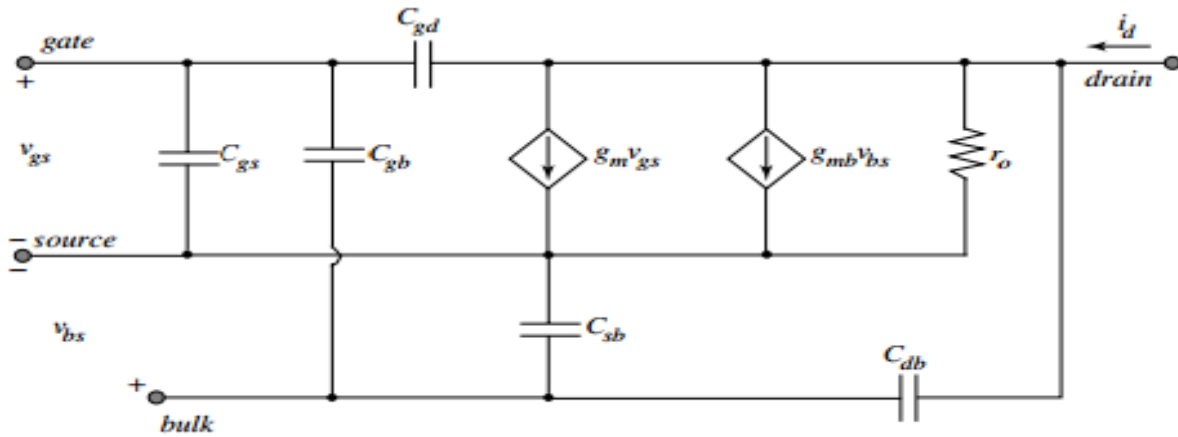## 2.1.4) SMALL SIGNAL ANALYSIS: THE QUADRATIC MODEL

Figure 2: Complete small signal model of MOSFET

The quadratic model uses the assumptions that the charge density in the inversion layer is constant between source and drain. However, this model allows the inversion layer charge to vary between the source and the drain. The derivation is based on the fact that the current is continuous throughout the channel. The current is also related to the local channel voltage, $I > V_C$. We now consider a small section within the device with width dy and channel voltage $V_C + V_S$. The current equation is as follows:

$$I_D = \mu C_{ox} \frac{W}{dy} (V_G - V_S - V_C - V_T) dV_C$$

(2.5.1)

where the drain-source voltage is replaced by the channel voltage. Both sides of the equation can be integrated from the source to the drain, so that y varies from 0 to the gate length, L, and the channel voltage, V_C varies from 0 to the drain-source voltage, V_{DS}.

$$\int_0^L I_D dy = \mu C_{ox} W \int_0^{V_{DS}} (V_G - V_S - V_C - V_T) dV_C$$

(2.5.2)

The drain current, I_D, is constant so that integration results in:

$$I_D = \mu C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right], \quad \text{for } V_{DS} < V_{GS} - V_T \tag{2.5.3}$$

The drain current first increases linearly with the applied drain-to-source voltage, but then reaches a maximum value. According to the above equation the current would even decrease and eventually become negative. The charge density at the drain end of the channel is zero at that maximum and changes sign as the drain current decreases. The charge in the inversion layer does go to zero and reverses its sign as holes are accumulated at the interface. However, these holes cannot contribute to the drain current since the reversed-biased p-n diode between the drain and the substrate blocks any flow of holes into the drain. Instead the current reaches its maximum value and maintains that value for higher drain-to-source voltages. A depletion layer located at the drain end of the gate accommodates the additional drain-to-source voltage. This behaviour is referred to as drain current saturation. Drain current saturation therefore occurs when the drain-to-source voltage equals the gate-to-source voltage minus the threshold voltage. The value of the saturated drain current, $I_{D,sat.}$ is then given by the following equation:

$$I_{D,sat} = \mu C_{ox} \frac{W}{L} \frac{(V_{GS} - V_T)^2}{2}, \quad \text{for } V_{DS} > V_{GS} - V_T \tag{2.5.4}$$

The quadratic model explains the typical current-voltage characteristics of a MOSFET, which are normally plotted for different gate-to-source voltages. The saturation occurs to the right of the dotted line which is given by $I_D = \mu\, C_{ox}\, W/L\, V_{DS}^2$.
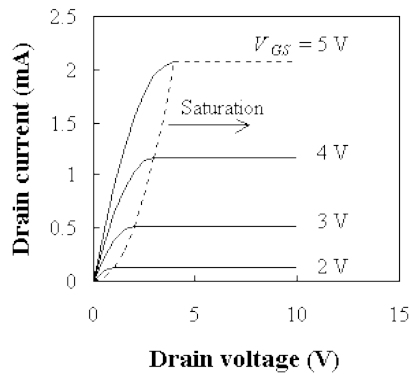

Figure 3: Current-Voltage characteristics of an n-type MOSFET as obtained with the quadratic model. The dotted line separates the quadratic region of operation on the left from the saturation region on the right.

The drain current is still zero if the gate voltage is less than the threshold voltage.

$$I_D = 0, \quad \text{for } V_{GS} < V_T \tag{2.5.5}$$

6

For negative drain-source voltages, the transistor is in the quadratic regime and is described by equation (2.5.3). However, it is possible to forward bias the drain-bulk p-n junction. A complete circuit model should therefore also include the p-n diodes between the source, the drain and the substrate. We now use the quadratic model used to calculate some of the small signal parameters, namely the trans-conductance, g_m and the output conductance, g_d or g_0. The trans-conductance quantifies the drain current variation with a gate-source voltage variation while keeping the drain-source voltage constant, or:

$$g_m \stackrel{\Delta}{=} \frac{\partial I_D}{\partial V_{GS}}\bigg|_{V_{DS}}$$

(2.5.6)

The trans-conductance in the quadratic region is given by:

$$g_{m,quad} = \mu C_{ox} \frac{W}{L} V_{DS}$$

(2.5.7)

which is proportional to the drain-source voltage for $V_{DS} < V_{GS} - V_T$. In saturation, the trans-conductance is constant and equals:

$$g_{m,sat} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T)$$

(2.5.8)

The output conductance quantifies the drain current variation with a drain-source voltage variation while keeping the gate-source voltage constant, or:

$$g_d \stackrel{\Delta}{=} \frac{\partial I_D}{\partial V_{DS}}\bigg|_{V_{GS}}$$

(2.5.9)

The output conductance in the quadratic region decreases with increasing drain-source voltage:

$$g_{d,quad} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T - V_{DS})$$

(2.5.10)

and becomes zero as the device is operated in the saturated region:

$$g_{d,sat} = 0$$

(2.5.11)

The measured drain current in saturation is not constant as predicted by the quadratic model. Instead it increases with drain-source voltage due to channel length modulation; drain induced barrier lowering or two-dimensional field distributions. A simple empirical model, which considers these effects, is given by:

$$I_{D,sat} = \mu C_{ox} \frac{W}{L} \frac{(V_{GS} - V_T)^2}{2} (1 + \lambda V_{DS}), \quad \text{for } V_{DS} > V_{GS} - V_T$$

(2.5.12)

Where λ is a fitting parameter.

2.2) SOFTWARE REQUIREMENTS: COMSOL Multiphysics® 4.4
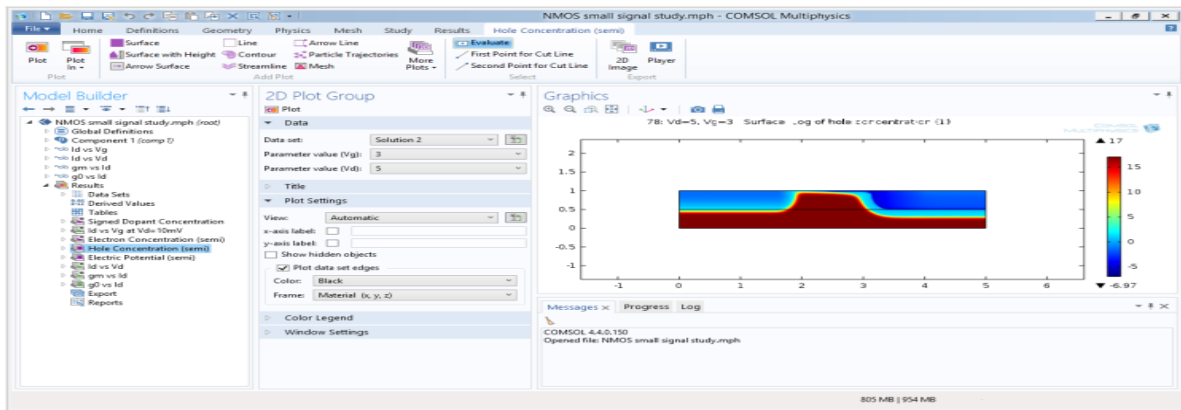

Figure 4: Snapshot of COMSOL MULTIPHYSICS 4.4

COMSOL is the platform for Physics-Based Modelling and Simulation

The COMSOL Desktop is a powerful integrated user interface environment designed for cross-disciplinary product development with a unified workflow for electrical, mechanical, fluid, and chemical applications.

2.2.1) Coordinate Systems

Users enjoy the ability to define any number of local coordinate systems. There are shortcuts for common coordinate systems such as cylindrical, spherical, and Euler-angle based, and a method for automatic coordinate system creation makes it easy to define anisotropic material properties that follow curved geometric shapes. This curvilinear co-ordinates tool, included in COMSOL Multiphysics, can be applied for any type of physics, like anisotropic thermal conductivity in heat transfer, orthotropic materials for structural mechanics, and anisotropic media in electromagnetic, for example.

2.2.2) Meshing and Finite Element Types

The meshing methods of COMSOL Multiphysics include free tetrahedral mesh, swept mesh, and boundary layer mesh.
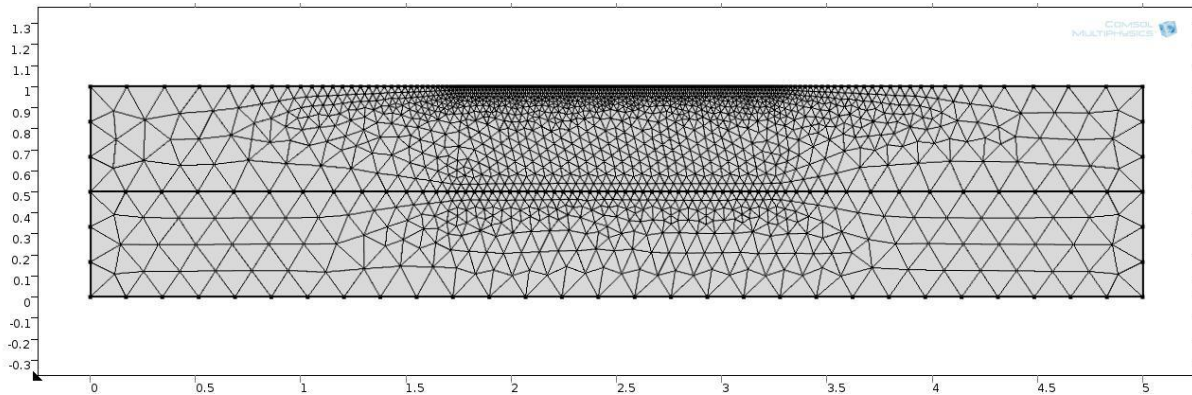

Figure 5: Physics controlled Mesh of a MOSFET

2.2.3) Geometry Modelling

COMSOL Multiphysics includes a geometry modelling engine that allows for parametric models in 1D, 2D, and 3D. More advanced geometry modelling is available with the CAD Import Module and the LiveLink products for CAD.

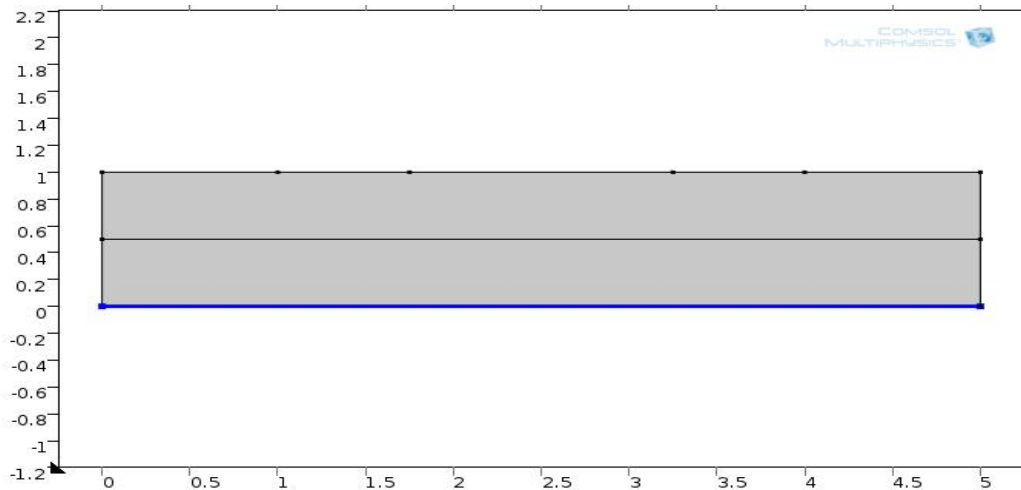
Figure 6: Geometry of MOSFET

2.2.4) Physics Builder

The Physics Builder, which is included in COMSOL Multiphysics, allows you to create your own physics interfaces accessible from the COMSOL Desktop® with the same look-and-feel as the built-

in physics interfaces. In the case of the Physics Builder, no programming is needed as you work directly in the COMSOL Desktop® from the Physics Builder Tree, defining new user interface components.

2.2.5) Verify and Optimize Simulation

COMSOL Multiphysics is a flexible platform that allows users to model all relevant physical aspects of their designs. Expert users can dig deeper and use their knowledge to develop customized solutions, applicable to their unique circumstances. With this kind of all-inclusive modelling environment, COMSOL gives you the confidence to build the model you want with real-world precision.

Characteristics of COMSOL become apparent with use. Compatibility stands out among these. COMSOL requires that every type of simulation included in the package has the ability to be combined with any other. This strict requirement mirrors what happens in the real world. Enforcing compatibility guarantees consistent multiphysics models and the knowledge that you never have to worry about creating a disconnected model again.

Another noticeable trait of the COMSOL Desktop® is adaptability. As modelling needs change, so does the software. The flexible nature of the COMSOL Desktop environment facilitates further analysis by making "what-if" cases easy to set up and run. We can take our simulation to the production level by optimizing any aspect of model. Parameter sweeps and objective functions for optimization can be executed directly in the user interface. From start to finish, COMSOL Multiphysics is a complete problem-solving tool.

3) METHODOLOGY

3.1) DEFINING PARAMETERS FOR MOSFET

Parameters for the study and computation of the conventional MOSFET are defined. These parameters are: Drain to Source Voltage (Vds or Vd), Gate to Source Voltage (Vgs or Vg), Frequency (freq), AC Voltage (Vac). Drain to Source Voltage is necessary to keep the drain current flowing in MOSFET. If small drain voltage is applied, a drain current proportional to Vds will flow from drain to source through the conducting channel. A positive Vgs is needed to create the conducting channel underneath the gate through which the drain current flows. Frequency and Vac are required to study the small signal analysis.

3.2) DESIGNING THE GEOMETRY OF MOSFET

The geometry of n-channel MOSFET is defined a solid rectangle (units are measured in μm). The coordinates for the source, drain, gate, and substrate are specified using the closed curve polygon.

3.3) MATERIAL SELECTION

A semiconductor material is selected. The materials used in this study are Silicon (Si), Germanium (Ge), Gallium Arsenide (GaAs) and Gallium Nitride (GaN).

3.4) SELECTION OF CARRIER DISTRIBUTION FUNCTION

Fermi Dirac distribution function for the carrier distribution is defined. It is also called as Fermi function, provides the probability of occupancy of energy levels by Fermions. Fermions are half-integer spin particles, which obey the Pauli Exclusion Principle. The Pauli Exclusion Principle postulates that only one Fermion can occupy a single quantum state. Therefore, as Fermions are added to an energy band, they will fill the available states in an energy band just like water fills a bucket. The states with the lowest energy are filled first, followed by the next higher ones. At absolute zero temperature ($T = 0$ K), the energy levels are all filled up to a maximum energy, which we call the Fermi level. No states above the Fermi level are filled. At higher temperature, one finds that the transition between completely filled states and completely empty states is gradual rather than abrupt.

Electrons are Fermions. Therefore, the Fermi function provides the probability that an energy level at energy, E, in thermal equilibrium with a large system, is occupied by an electron. The system is characterized by its temperature, T, and its Fermi energy, E_F. The Fermi function is given by:

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

3.5) DOPING OF MOSFET

The conduction in MOSFET is controlled by the doping. Doping replaces the semiconductor atoms with atoms that have a different electron configuration. For n-type doping, we replace the semiconductor atom with an atom for column V (P, As). For n-type doping, we replace the semiconductor atom with an atom for column III (B). Substrate is doped with p-type material. Then, Source and Drain are doped with p-type material. The n-wells are Gaussian type so as to properly define the region in which the n-type doping is to be done.

3.6) METAL CONTACTS

Metal contacts for the source, drain and substrate are defined. These contacts are ideal ohmic contacts. The Ohmic contact is a low resistance junction (non-rectifying) provides current conduction from metal to semiconductor and vice versa. Theoretically speaking the current should increase/ decrease linearly with the applied voltage. With an immediate response for the any small voltage. There are two types of the Ohmic contacts: Ideal nonrectifying barriers and tunnelling barriers.

In this type of contacts, thermal equilibrium occurs when electrons flows from the metal to the semiconductor lower energy levels. After the equilibrium, these electrons flow back into the metal part if a positive bias in the metal part was applied, and they will feel no barrier. Applying a negative bias forces electrons to flow from metal to semiconductor seeing a very small barrier.
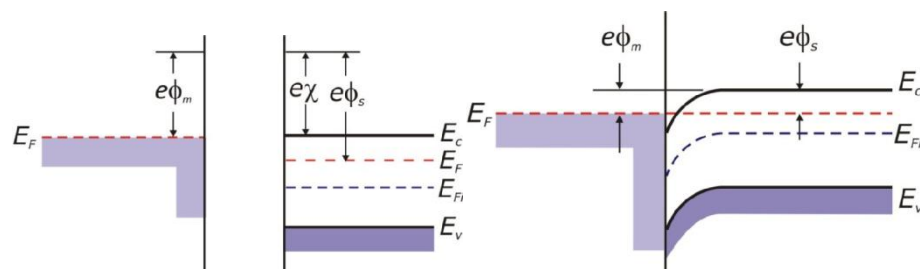

Figure 7: a) An ideal energy band diagram   b) After contact for a metal-n
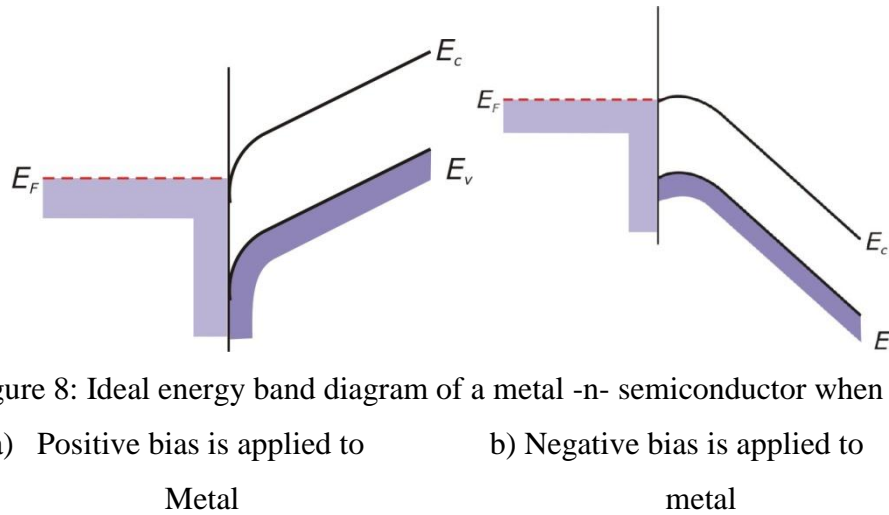before contact   semiconductor junction

12

Figure 8: Ideal energy band diagram of a metal -n- semiconductor when

a) Positive bias is applied to Metal

b) Negative bias is applied to metal

3.7) THIN INSULATOR GATE

Thin insulator gate is defined. Insulation is provided to the gate from substrate using a gate dielectric. The gate dielectric is subject to many constraints, including:

- Electrically clean interface to the substrate (low density of quantum states for electrons)
- High capacitance, to increase the MOSFET trans-conductance
- High thickness, to avoid dielectric breakdown and leakage by quantum tunnelling.

3.8) MODEL FOR GENERATION AND RECOMBINATION OF CARRIERS

The presence of impurities or crystal defects in semiconductors determines the lifetime of carriers, because a modified electronic structure within the crystal will give rise to defect levels, or energy levels that do not lie near the edge of the band gap. Deep defects may lie deep within the forbidden band; these impurity levels are also called trap levels because they are traps for charge carriers1. These levels can effectively facilitate a two-step recombination process called Shockley-Read-Hall recombination where conduction electrons can relax to the defect level and then relax to the valence band, annihilating a hole in the process.

After analysis of the dynamics involved in this process, we see that that the recombination rate R_T involved with traps is dependent on the volume density of trapping defects and the energy of the trapping level:

$$R_T = \frac{np - n_i^2}{\tau_{h0}(n + n_1) + \tau_{e0}(p + p_1)}$$

13

Where *n* and *p* are the concentrations of electrons and holes respectively, *ni* is the "intrinsic carrier concentration", **and τ_{h0} and τ_{e0} are** lifetime parameters (for holes and electrons respectively) whose values depend on the type of trap and the volume density of trapping defects. The quantities *n₁* **and *p₁*** are parameters that introduce the dependency of the recombination rate on the trapping energy level *Eτ* as follows:

$$n_1 = N_C \exp\left(\frac{E_t - E_c}{kT}\right)$$

$$p_1 = N_V \exp\left(\frac{E_v - E_t}{kT}\right)$$

$$n_1 p_1 = n_i^2$$

These expressions are of the same form as the charge carrier concentration in terms of the Fermi energy level; what we see is that if τ_{h0} **and** τ_{e0} are of the same order of magnitude, the peak value for this type of recombination will occur when the defect level lies near the middle of the forbidden band gap. Therefore, impurities that introduce energy levels near mid-gap are very effective recombination center.

Another way in which crystal defects come into play is at the surface of semiconductors, where there are an abundance of such defects that introduce defect levels for trapping. Therefore, this process of recombination by defect levels contributes significantly to recombination at surfaces.

3.9) DEFINING MESH

Mesh model describes the degree of freedom of charge carriers. The probability of finding charge carriers is maximum at the corners.

3.10) AC-DC ANALYSIS

DC analysis of a MOS (metal-oxide semiconductor) transistor: In normal operation, a system turns on a MOS transistor by applying a voltage to the gate electrode. When the voltage on the drain increases, the drain current also increases until it reaches saturation. The saturation current depends on the gate voltage. DC analysis of MOSFET includes:

- Drain characteristics- Plot of drain current versus drain-source voltage with constant gate-source voltage.

- Transfer characteristics- Plot of drain current versus gate-source voltage with constant drain -source voltage.

The small-signal analysis is a mathematical approximation that allows to see the effect of incremental changes on the inputs of an electrical device on its output characteristics. For the MOSFET, two small signal outputs are particularly interesting to get as they provide information on the device performances. Those are the trans-conductance and the output conductance.

- Trans-conductance –Trans-conductance is a property of certain electronic components. Conductance is the reciprocal of resistance; trans-conductance is the ratio of the current variation at the output to the voltage variation at the input.
- Output Conductance - The output conductance quantifies the drain current variation with a drain-source voltage variation while keeping the gate-source voltage constant.

3.11) COMPARISON OF DIFFERENT SEMICONDUCTOR MATERIAL MOSFET

Different materials are compared on the basis of parameters like trans-conductance, output conductance, input and output characteristics. The results are shown later in the report.

4) GRAPHENE

Carbon, the 6th element in the periodic table, is one of the most fascinating elements in the world. It is the basis of life.

There are two kinds of bulk carbon crystals known as of now: diamond and graphite. Graphene is the sub type of Graphite that was discovered recently. Graphene is a new wonder material.

Graphene is one layer of carbon atoms in natural Graphite. Graphene is a semimetal because the conduction band and valence band is touching. It can also be called a semiconductor with zero band-gap. It is thought to have amazing properties. The unique feature is that it integrates all these extraordinary electrical, optical and mechanical properties into one material. No other material can compete in this regard.

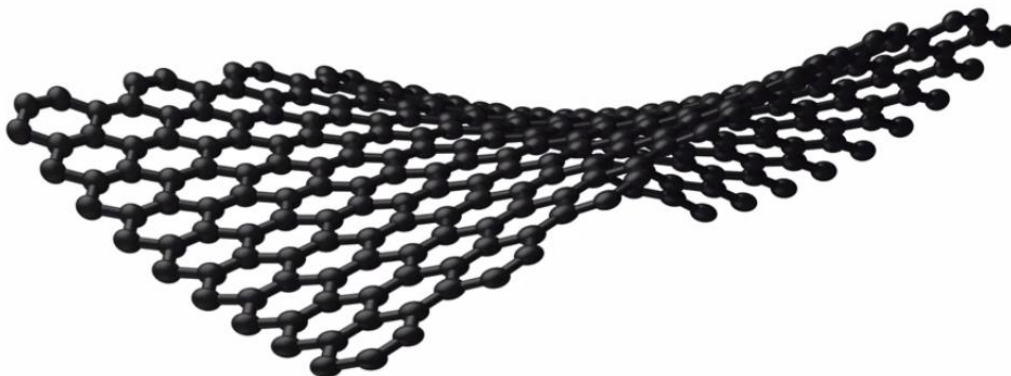But to produce a single layer of atoms on an insulator so as to measure the properties is extremely difficult.

Figure 9: Graphene

Andre Geim and Konstantin Novoselov, researchers at the University of Manchester, were among those scientists who were looking hard for methods to isolate graphene.

They were driven by the idea to observe the electric field effect in metals, which meant they wanted to change the conductivity by applying an electric field to adjust the electron density.

They wanted to observe the field effect in phenomena in metals. However, it is difficult because the density of electrons in metals is much larger than in semiconductors.

Therefore, one has to reduce the thickness of the metal to reduce the amount of electrons. But ordinary metals will mechanically break before they are atomically thin. So, Geim and Novoselov thought of graphene which is a "semimetal".

They tried several ways to reduce the thickness of graphite, such as mechanical polishing, but could only reach a thickness of about 10 micrometers.

Then, one Friday evening in 2004, these scientists decided to use scotch tape to produce a few layers of graphene. When they had the material they immediately fabricated some devices and for the first time observed the electric field effect in it.

Graphene-like structures were already known of since the 1960's but there were experimental difficulties in isolating single layers in such a way that electrical measurements could be performed on them, and there were doubts that this was practically possible.

It is interesting to consider that everyone who has used an ordinary pencil has probably produced graphene-like structures without knowing it. A pencil contains graphite, and when it is moved on a piece of paper, the graphite is cleaved into thin layers that end up on the paper and make up the text or drawing that we are trying to produce. A small fraction of these thin layers will contain only a few layers or even a single layer of graphite, *i.e.* graphene.

Thus, the difficulty was not to fabricate the graphene structures, but to isolate sufficiently large individual sheets in order to identify and characterize the graphene and to verify its unique two-dimensional (2D) properties. This is what Geim, Novoselov, and their collaborators succeeded in doing.

One year later the similar effect was observed in monolayer graphene. A few years later (in 2010) they were awarded the Nobel Physics prize.

4.1) ATOMIC STRUCTURE

The graphene lattice looks almost like the 2-D Hexagonal Bravais lattice except that there are no atoms in the center of the hexagons. The atoms are classified into two types according to their positions. Atom A has 3 B atoms surrounding it: one is at the upper left, one at the lower left, and one to the right. Atom B is also surrounded by 3 A atoms, but the positions are different: one to the left, the other two are at the upper right and lower right directions, respectively. In physics, it is known as complex lattice, where atoms A and B form the sub lattices.
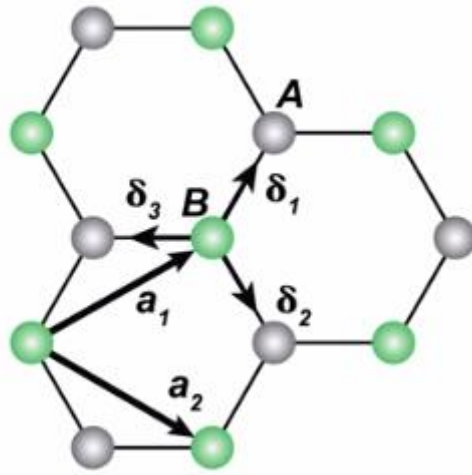
Figure 10: Structure of Monolayer Graphene

But if only one type of atom is taken into consideration, then they form hexagon with one atom at the center, which is the Hexagonal Bravais Lattice.

The three vectors δ_1, δ_2 and δ_3 are the distance from atom B to the neighbouring atom A (or vice versa) and the length of these vectors is calculated in the terms of the nearest neighbour distance a. The vectors a1 and a2 are the distance of atom B (or A) to the centre atom B (or A) of sub lattice. The lattice vectors a1 and a2 and they are the basis for graphene's parallelogram primitive unit cell. The length of these two vectors is called the lattice constant of graphene.
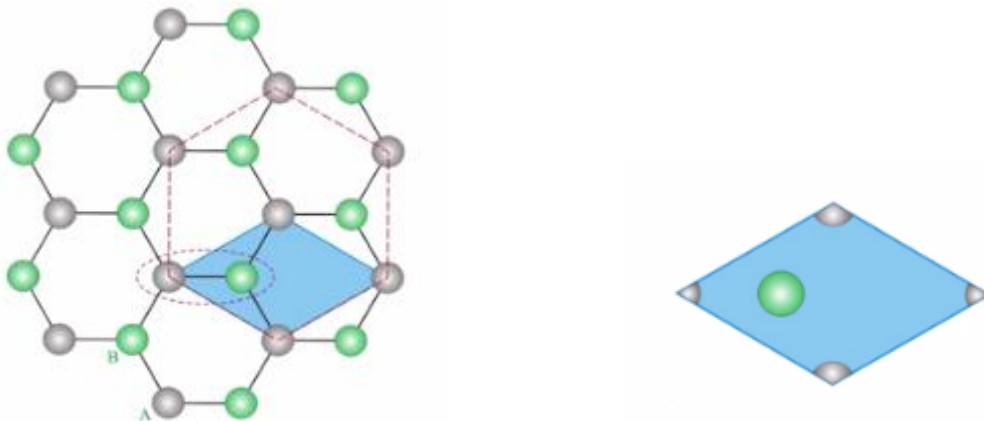

Figure 11: Formation of Primitive cell where only one atom of each type is contained

The values of these vectors are:

$$\vec{\delta}_1 = \frac{a}{2}(1, \sqrt{3}),$$

(4.2.1)

18

$$\vec{\delta}_2 = \frac{a}{2}(1, -\sqrt{3})$$

(4.1.2)

$$\vec{\delta}_3 = a(-1, 0)$$

(4.1.3)

$$\vec{a}_1 = \frac{a}{2}(3, \sqrt{3})$$

(4.1.4)

$$\vec{a}_2 = \frac{a}{2}(3, -\sqrt{3})$$

(4.1.5)

Carbon is the 6th element in the periodic table, which means it has 6 electrons.

Electrons in an atom have different energies. Those with lower energies are closer to the nucleus and those with higher energies are able to be farther away from the nucleus. Electrons prefer to fill in the states with lower energies first, just like water always wants to flow towards lower places to reduce its energy. However, when these states are fully occupied then the other electrons have no choice but to go to the higher energy states.

In the first electron shell of the Carbon atom, there are 2 electrons. This shell can only contain 2 electrons and therefore the rest 4 electrons will have to be placed in the second electron shell. This shell can be further divided into 2 subshells, one is called 2s and the other called 2p containing p_x, p_y, and p_z. Sub-shell 2p is of slightly higher energy than 2s. Each box can contain 2 electrons with different spins. The arrows mean spin up or spin down of the electron. In the second electron shell there can be at most 8 electrons in total, so there are still 4 spaces left.
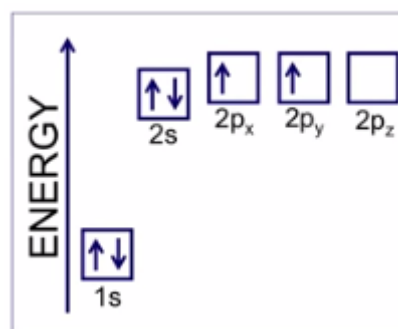

Figure 12: Electronic Configuration of Carbon Atom

Quantum mechanics calculation points out that the electrons are moving without any orbits. They appear randomly around the nucleus. The orbits we draw are just the positions where the electrons have somewhat greater probabilities to appear. These random movements result in the so called

19

electron clouds. The shape of electron clouds for the p sub-shell electrons is like a spindle which corresponds to the positions where the electron has greater possibilities to be found. In atoms, when a shell is partly occupied it is not stable.
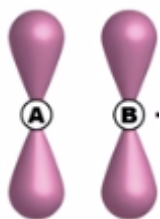

Figure 13: Spindle shaped p electrons

The atoms have a tendency to have the shell either completely filled or emptied. There are 4 spaces left in the second electron shell. Therefore, each carbon atom has to fetch 4 extra electrons from somewhere else.

A chemical bond *between* two electrons can be formed in two ways: Sigma (σ) covalent bond and Pi (π) covalent bond. In Sigma bond, the atoms share two electrons with each other. In Pi bond, the two electron clouds are in parallel and they superimpose with each other in the "shoulder to shoulder" fashion rather than "head to head". The electron cloud in σ bond is heavily overlapped whereas π bond is only slightly overlapped. As a result, σ bond is more stable and not very reactive while π bond is less stable and more reactive.

Each atom Carbon can form 2 covalent bonds with neighbouring atoms because each carbon atom has 2 electrons in the p sub-shell. The two bonds should have 90 degree angle because this is the angle between the p_x and p_y orbits. But that is not the case in reality.
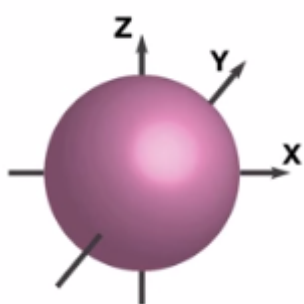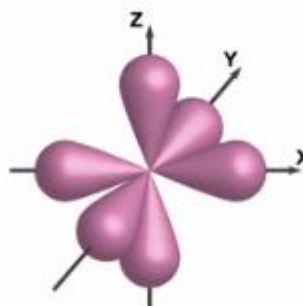

Figure 14: a) 2s orbit   b) 2p orbit

Actually, each carbon can form 4 bonds because the two electrons in the s sub-shell can also participate in the bond formation. The carbon atom will get 4 electron pairs and therefore in each atom there will now be 8 electrons in its second electron shell. The four vacancies in this shell are

completely filled and the atom is satisfied. This works on the Pauli's Hybrid Orbital Theory which states that atomic orbits with similar energies can form new hybrid orbits. That is, although 2s sub-shell has slightly lower energy compared with 2p sub-shell, 2s and 2p electrons can form hybrid orbits while they are forming covalent bonds with neighbouring atoms.

For carbon atoms there are 3 types of orbital hybridization. They are sp1, sp2 and sp3 hybridization. There small numbers at the superscript tell us how many electrons are there in the orbits.
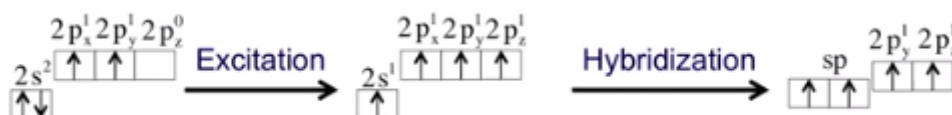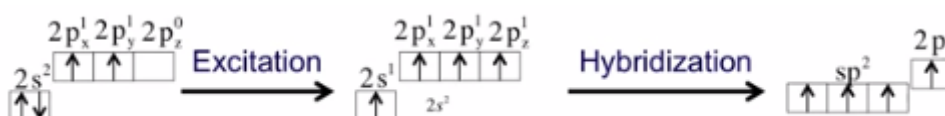

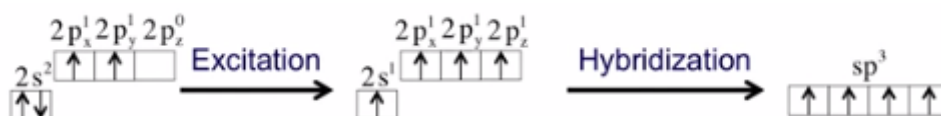Figure 15: sp or sp1 hybridization

Figure 16: sp2 hybridization

Figure 17: sp3 hybridization

In graphene, the 3 sp2 electrons can form 3 bonds with neighbouring atoms. These bonds are σ bonds and they are very stable, one of the strongest chemical bonds in nature. The 3 σ bonds are in the basal plane. The 3 sp2 bonds are identical so their angles are 120 degrees. The 2p electron that is left is called the π electron as it forms π bond with other carbon atoms in graphite. However, this π bond is delocalized which means the π electron is shared among all atoms in the layer. This quasi-free π electron is responsible for graphene's electrical conductivity.

Sometimes people can regard the graphene sheet as a super large molecule. These super large molecules are stacked on top of each other to form graphite. The van der Waals force between layers is the origin for the interlayer cohesive force in graphite.

In a graphene lattice we have a spatially periodic signal, which is made up by the lattice points where the carbon atoms sit. We start from the lattice points in one unit cell. If we shift that unit cell by a lattice vector then we get another unit cell. Repetition of this translational operation will generate all the lattice points.

After doing the Fourier transform of the graphene lattice, we get the lattice in k space. After the transform, we get another set of periodically arranged points called the reciprocal lattice. This is also a hexagonal lattice and the primitive unit cell is also a parallelogram. The lattice vectors in the real and reciprocal spaces are denoted by a1, a2, and b1, b2, respectively. The reciprocal lattice can be achieved simply by rotating the direct lattice by 90 degrees. But one should always remember that the unit in the reciprocal lattice is 1/length, and it is a momentum space or state space.

Figure 18: a) Direct Lattice   b) Reciprocal Lattice

In the reciprocal lattice of graphene, the primitive unit cell is outlined by the dashed line. In this parallelogram we only have one reciprocal lattice point because the lattice points at the 4 apexes only partially belong to this parallelogram.
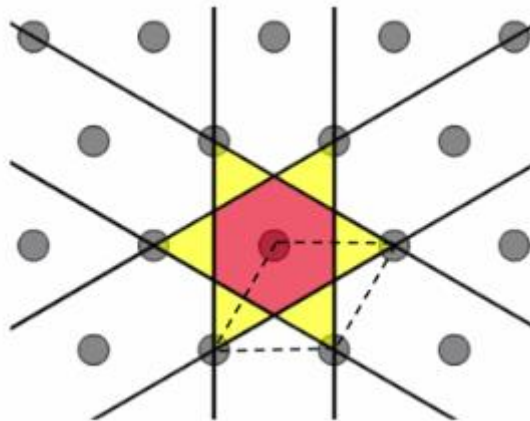

Figure 19: Enhanced view of the reciprocal lattice

However, there is another way of choosing the primitive unit cell. If we draw 6 lines as shown in fig., then the hexagon in the middle is called the first Brillouin zone. This zone is more symmetric than the parallelogram, and the reciprocal lattice point is exactly in the center. This lattice point is often set to be the origin of the coordinate system in the reciprocal lattice. The yellow regions are called the second Brillouin zone. We can define the third and fourth Brillouin zone as well but they are farther away from the origin and are rarely used. The area for the first and second Brillouin zones both equal to that of the parallelogram. The six corners of the first Brillouin zone are called the Dirac points. They are very important in graphene. The k space is rather abstract, but it is widely

used in solid state physics to study many physical quantities and phenomena. k is the wave number which can be regarded as the spatial frequency. It is related to the reciprocal of the wavelength, the quasi momentum, and the states of particles. It is linked to the real space by the Fourier transform.

4.2) BANDGAP FORMATION

Theoretical physicists have calculated the energy band of monolayer graphene by using the so-called tight-binding model. The energy dispersion relation is:

$$E(\vec{k}) = \pm t\sqrt{3 + f(\vec{k})}$$

(4.2.1)

where,

$$f(\vec{k}) = 2\cos(\sqrt{3}k_y a) + 4\cos(\frac{\sqrt{3}}{2}k_y a)\cos(\frac{3}{2}k_x a)$$

(4.2.2)

Here t is an energy parameter whose value can be obtained by fitting the results of more sophisticated first-principle numerical calculations. The value of t can vary in literature, but is usually within the range from -3.3 to -2.7 eV.

The E-k dispersion relation is plotted in the first Brillouin zone for our own convenience. The vertical axis is the energy and the horizontal axes are kx and ky.
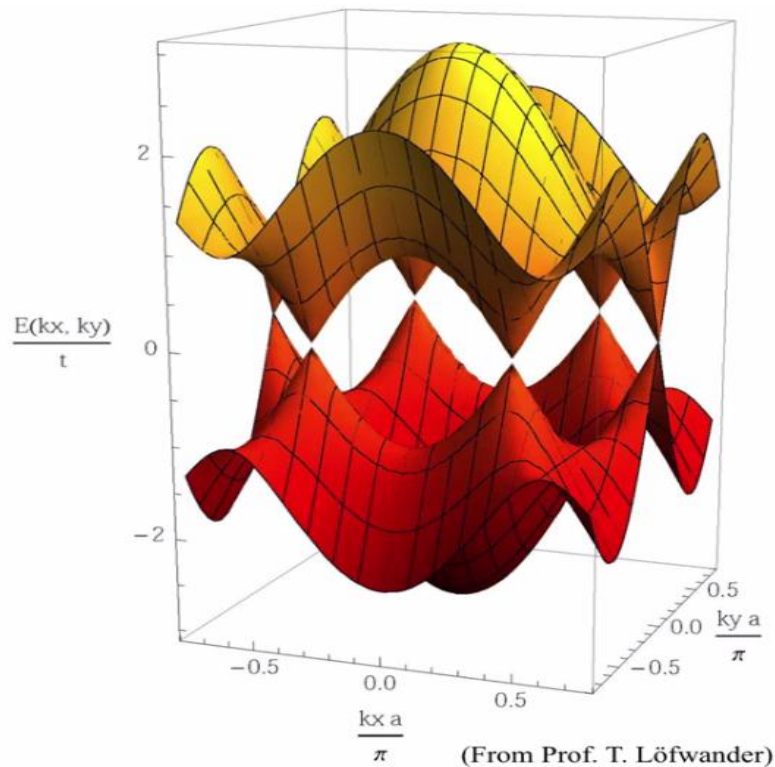
Figure 20: E-k Dispersion plot in K-space

The curved surface of the plot composes of two parts. Upper part is the conduction band and the lower part is the valence band. These two bands are both for the π electron of graphene. Carbon atoms in graphene have 4 electrons in the outer electron shell, where 3 of them are sp2 hybridized and form σ bonds with neighbouring atoms. The 4th electron is the π electron here. This electron has higher energy and is quasi free. It is shared among all the carbon atoms in graphene, and is responsible for graphene's electrical conductivity. The other electrons are not that active and are more confined to their own atoms and do not contribute to the properties of Graphene much.

For intrinsic graphene, the Fermi level is exactly at the place where the conduction band meets the valence band. There are in total 6 such points, which we call the Dirac points. These 6 Dirac points are evenly distributed in the same plane, which is the surface of the Fermi sea.

The band structure decides that graphene is a conductor, because if we regard the two bands as a whole, then it is only half filled. Practical graphene is always more or less doped, which means its Fermi level can be shifted above or below the Dirac points.
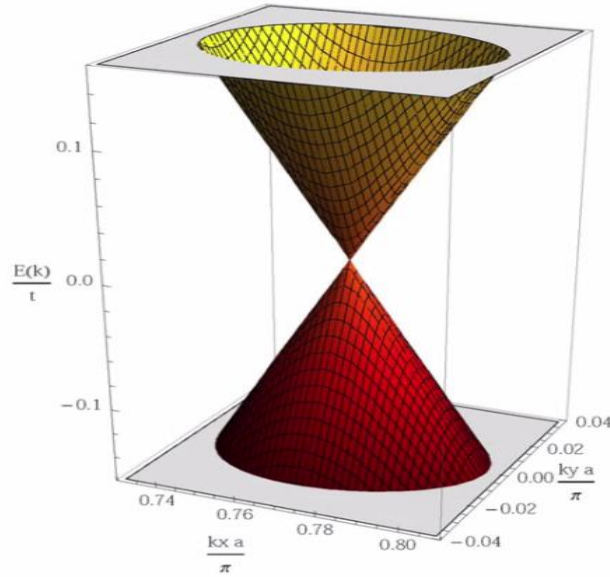
Figure 21: Zoomed-in image of Dirac Cone

Near the Dirac Points, the shape of the E-k Dispersion plot becomes like a cone. It is also known as the Dirac cone. When the energy is not far away from the Dirac Points, the cone becomes circular and the E-k dispersion shows a linear dependence. This is quite unique as in many other materials, the dispersion is parabolic.

The linear dispersion for graphene is valid within approximately ±0.6 eV of the Dirac points. It also results in the so called mass-less Dirac particles in graphene, which means the (effective) rest mass of electrons is 0 in graphene. It is because these electrons follow the Dirac equation where the special theory of relativity plays a role. In fact, the dispersion can be written as:

$$E(\vec{k})^{\pm}_{linear} = \pm\hbar \left|\vec{k}\right| v_F$$

(4.2.3)

where,

$\hbar\vec{k}$ is the quasi momentum relative to the Dirac Point and vF is the velocity at which electrons move

and

$$v_F = \frac{3a|t|}{2\hbar} \approx 10^6 \, \text{m/s} \approx c/300$$

(4.2.4)

As they can be described by similar mathematical equations, electrons in graphene behave similar to photons, but at a much lower speed. That is, unusual properties of quantum electrodynamics

25

where relativity effects are relevant can be observed without the need to accelerate the particles close to the speed of light.

4.3) PROPERTIES

The unique feature in Graphene is that it integrates all these extraordinary electrical, optical, mechanical… properties into one material. No other material can compete in this regard. Like many other nano-materials, graphene is also an important playground for fundamental studies such as quantum Hall physics, electrodynamics where the theory of relativity plays a role, etc. What is unique is also that graphene demonstrates its high potential in applications already at this early stage. This is because it is 2-dimensional which is easier to process compared with 1- and 0-dimensional nano-materials. Since graphene is made of carbon the cost could also potentially be very low.

4.3.1) ELECTRICAL PROPERTIES

Graphene is a semimetal, which means it is not a metal but behaves more or less like a metal and therefore it is a conductor.

In the graphene lattice, electrons can travel with only little scattering. That is, electrons can easily be accelerated to high speeds. We use the carrier mobility μ to describe this. Carriers mean electrons and holes. The mobility is the drift velocity v of electrons divided by the external electric field E. It is theoretically estimated that graphene should have a room temperature mobility of about 2×10^5 cm^2/(Vs). Impressively, this has also been shown, although under very stringent experimental conditions.

Materials	μ (cm^2/(Vs))
Si	1000-2000
GaAs	9000
InP	5000-7000
InAs	33000
InSb	78000

Table 1: Carrier Mobility of common materials

The conductivity is determined by mobility and carrier density:

σ=neμ, where n, e and μ are carrier density, elementary charge, and mobility, respectively.

Comparing graphene with copper which is one of the best conductors, the conductivity for graphene is about 35% higher than for copper. As we know metals usually have a high electron density, therefore graphene can beat copper mainly thanks to its super high mobility.

At room temperature, the intrinsic electron and hole density for graphene is therefore about 9×10^{10} cm^{-2}.

4.3.2) OPTICAL PROPERTIES

Most conductors such as metals are optically opaque. That is because the free electrons in the conductors have a screening effect, preventing the photons to pass through. But graphene is an exception. It is one of the few transparent conductors known to us. It is just one atom thick and each layer only absorbs 2.3% of the incident light. This number is calculated theoretically based on the electrodynamics of graphene's electronic structure.
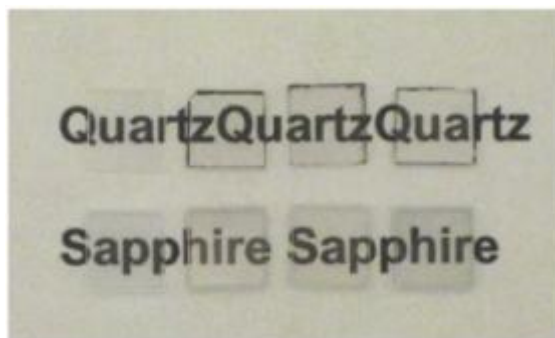

Figure 22: Samples of quartz and sapphire with no or some monolayer graphene

In each row of the figure, the far-left sample is bare quartz or sapphire sample, while the other three identical samples are the same type of quartz or sapphire substrates with monolayer graphene. The samples are placed on a piece of paper with a text on it. The text is clearly seen through the samples due to the high transparency of the graphene. Quantitative measurements show that after the addition of graphene, the transmittance of the quartz sample is reduced by 2-3%, which is in agreement with the theory. Another amazing optical property is that its transparency is roughly independent of the wavelength of the light. It is transparent from infrared all the way to the ultraviolet regime.
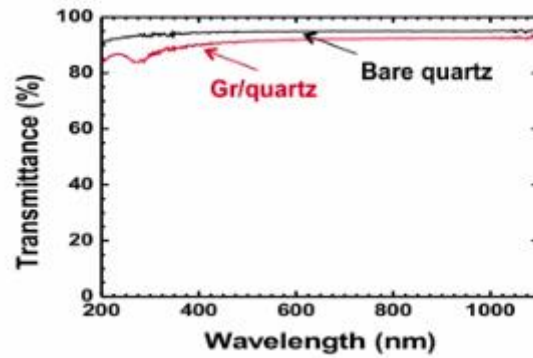
Figure 23: Transmittance Plot for Bare quartz and quartz with monolayer Graphene

The transmittance of graphene is almost independent of the wavelength of the light. Many other transparent materials, glass for example, is not transparent to UV light.

4.3.3) THERMAL PROPERTIES

Graphene is an excellent thermal conductor. Its intrinsic thermal conductivity is the highest among all materials, even higher than diamond. Thermal conductivity is greater than 3000W/m/K at room temperature. It has been shown that the thermal conductivity is isotropic within the basal plane which means that it is the same in every direction.

4.3.4) MECHANICAL PROPERTIES

Graphene is only 0.34 nm thick. It is the thinnest material ever till date. Amazingly, it has distinct mechanical properties.

The breaking strength of graphene is as high as 130 GPa, which is about 100 times greater than steel. Breaking strength means the pressure at which you can pull the material apart. It is the pressure, and not force. So we have to normalize it to the cross-sectional area of the material. Therefore graphene is the strongest material in the world.
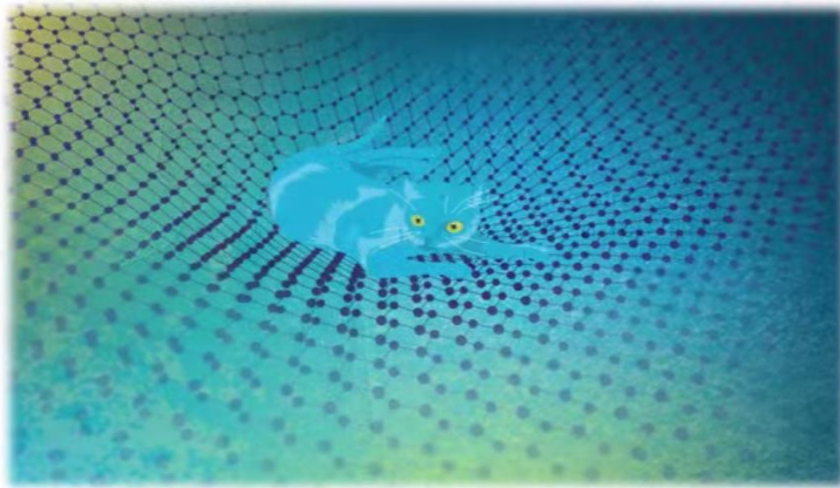
Figure 24: The proposed sheet of graphene enough to support the weight of the cat

By a simple calculation we know that for a perfect piece of graphene, if we could make it into a 1 m^2 hammock, it would support the weight of a cat of 4 kg.

Graphene is very stretchable, up to 20% of its initial length and also completely flexible due to its atomic thickness.

4.3.5) CHEMICAL PROPERTIES

Graphene is chemically rather stable. The sp2 bonds in graphene are one of the strongest in nature. Its bond energy is 607 kJ/mole, even higher than that of diamond: 347 kJ/mole. It cannot easily be attacked by acids and bases, although very strong acids and bases do modify graphene's properties to some extent. At room temperature it is also rather stable with Oxygen, but at high temperatures of around 700 degrees graphene is completely burnt into CO_2.

The surface of graphene is relatively easy to modify with oxygen- and nitrogen-containing functional groups, which means that graphene's chemical properties can be tailored.

It has been employed as a substrate to be interfaced with various bio-molecules and cells.

Some research point out that graphene is largely biocompatible, but this is still debatable and under investigation.

4.4) ADVANTAGES AND DISADVANTAGES

Graphene has many extraordinary properties, including the electrical, optical, thermal properties, etc. The very unique thing here is that all these properties are integrated in one material. You can find materials that are as conducting or as transparent as graphene, but you can hardly find any materials that are simultaneously electrically conducting, optically transparent and mechanically flexible. Also the transparency for graphene covers a wide range of the optical spectrum, from infrared all the way to ultraviolet.

Graphene has a high potential in both fundamental research and applications. Graphene offers a nice playground for fundamental studies in quantum mechanics such as room temperature quantum Hall effect, relativity effects such as mass-less Dirac Fermions, and so on.

At the same time, downstream graphene products are already on the market, only after about 10 years since graphene was first isolated.

Graphene is just a form of carbon, which is the 4th most abundant element in the universe. So it is abundant, cheap, eco-friendly and sustainable.

Whenever we introduce a new material, its compatibility with traditional materials and processing is always a concern. After more than half a century of development, Si based technology has been dominating the electronics industry, and it is based on planar processes on large area Si wafers.

Fortunately, graphene is 2-dimensional and therefore its planar structure is compatible with traditional semiconductor processing, and can be relatively easily integrated into the existing mainstream technology.

Like everything has two sides, there are certainly some challenges for graphene technology.

An ant can carry things that are about 50 times their own weight. That is far beyond what humans can do. But, we have to be aware that we are scaling down the humans for the comparison. At their scale, we are much weaker than the ants. But this scaling down is imaginary; if we consider the absolute values then humans are still stronger than ants! The same thing is true when we talk about graphene. Graphene is much stronger than steel if we normalize steel to atomic scale. In fact it is not certain that the steel will remain continuous if we keep on thinning it down to one atomic layer. So, when you are building a burglary-proof door for your house you should probably choose steel instead of graphene.

Silicon is successfully being used in electronics since past 70 years. In fact, Si is not a wonderful material in terms of properties. The carrier mobility is not high, the conductivity is modest, and it

cannot easily emit light due to its indirect energy band-gap. However, at least Si is very cheap and it has a high quality native oxide which is SiO_2. The raw materials for producing Si come from stones and sand. Silicon's native oxide has a high quality interface with Si, which is very good for device insulation and passivation. These properties compensate the gap when comparing Silicon with other good semiconductors.

The two major advantages of Si are missing in graphene. So far the price for graphene is still high, although potentially it can be quite low. A piece of 1 cm^2 graphene grown by chemical vapour deposition and transferred to a SiO_2 substrate typically costs 50 Euros. It is possible to buy even cheaper graphene at the moment, but at the sacrifice of quality.

Graphene is rather sensitive to its environment. This is generally a drawback when making devices expect for sensors. Up to now there are no effective passivation methods for protecting graphene electronic devices against moisture, temperature, and oxidation from the environment. Many protection layers are also affecting the device properties at the same time. Fortunately, the cost and sensitivity issues are not intrinsic in graphene.

Considering that graphene technology has only a history of around 10 years, we expect this could be solved with time.

High quality thin graphene film production is still lacking in reproducibility and the yield is not high so far. For graphene produced by chemical vapour deposition, the transfer of graphene from its original metal catalyst foil to an insulating substrate is still irreproducible. Holes, wrinkles and other damages can happen. It is not easy to obtain uniformly bi-layer or tri-layer graphene in large areas. The controllability of the graphene thickness is still low.

Graphene is the most conducting at monolayer scale. However in reality it has to compete with other materials that are tens of or even hundreds of nm thick. In this case the sheet resistance of graphene is often not satisfactory. An effective doping strategy is yet to be developed to reduce the sheet resistance.

Finally, graphene is a semimetal with no band-gap. In other words, it is not a semiconductor, which is an advantage for many applications, but not for transistors. A transistor requires the channel material to have a large enough energy band-gap so that the charge carriers have the possibility to be depleted. If not, it implies that the transistor cannot be turned off and will always consume power. Scientists are trying hard to open a gap in graphene. For example, one can make the graphene into nano-ribbons. The quantum confinement effect will help to open a band-gap, but it is still under development.

Graphene is indeed a unique material that combines many extraordinary properties. Therefore it will have a great impact on our future life. However, as scientists we should also recognize the challenges objectively. Fortunately, most challenges are not intrinsic, which are expected to be solved or improved during the continued development of the graphene technology beyond its history of merely 10 years.

4.5) APPLICATIONS AND FUTURE SCOPE

Graphene's possible applications can roughly be categorized into 6 groups: transparent conductors in optoelectronics, integrated circuits, energy applications, sensors and actuators, composite materials, and biological applications. This is not the end of the list as it is endless and have application in almost every field of technology.

The closest application is touch screen, rollable e-paper and OLEDs. One of the reasons is that the technical barrier for graphene to enter the microelectronics and optoelectronics field is relatively low.

4.5.1) OPTOELECTRONICS

Graphene plays an important role in optoelectronics. In this field, a transparent conductor is often needed as the electrode material. An electrode should of course conduct current as much as possible, and at the same time it should be transparent so that light can pass through. The high conductivity, high mobility, high transparency (2.3%/layer), high chemical stability, high flexibility and high mechanical strength of graphene, together with the wide optical spectrum range in wavelength, makes graphene one of the best transparent conductors for optoelectronics.

It can be used in light emitting diodes (LEDs) which are key elements for solid state lighting in our future society since LEDs are much more efficient than traditional Incandescent light bulbs. Here LEDs include both conventional semiconductor LEDs and new organic LEDs, which we call OLEDs.

Graphene can be used in touch screens, which are almost everywhere in consumer electronics. It is very likely that our future mobile phones, computers are flexible, where graphene will contribute significantly.

Apart from these devices that emit light, graphene can also be used as transparent electrode on devices that absorb light, such as photo-detectors, solar cells, etc.

The main stream transparent conductor used in the industry is indium tin oxide (or simply ITO), which is a doped semiconductor. It contains indium which is very scarce and the price will be increasing. Also the material is brittle and not transparent for UV light. On the other hand, graphene is abundant and potentially with low cost. Graphene is eco-friendly and sustainable, and can be produced in large area.

The technical threshold for graphene to be competitive in optoelectronics business is relatively low, as compared with transistors in integrated circuits. A typical touch screen only requires roughly 85% transmittance and 200-300 $\Omega/\square$ sheet resistance. Therefore, it should not be overoptimistic to imagine that graphene can be widely used in commercial optoelectronic devices in 5-10 years.

4.5.2) INTEGRATED CIRCUITS

Integrated circuits (ICs) are the basis for our modern information society. Computers, mobile phones, etc. are all based on IC.

The key element in integrated circuits is the transistor, meaning a tunable resistor that can amplify and switch electronic signals and electrical power. Currently most transistors are made of silicon.

From the definition of mobility, we can see that under a given electric field, electrons in graphene can drift with a higher velocity than in silicon. Therefore, graphene is promising in serving as the channel material for ultrafast transistors and might play a key role in IC. However, we cannot claim that graphene can do better than or replace silicon in IC in the near future. That is because graphene is not a semiconductor. An ideal transistor should be made from semiconducting material so that the current can be switched off. If a transistor cannot turn off then it will consume more electricity and our computers will become very hot. Currently, scientists are trying hard to open an energy band-gap in graphene so that the ultrafast graphene transistors can be turned off.

At the same time, people are looking for opportunities to use graphene in passive elements in IC, such as heat spreader and interconnect wires. Electronic and photonic systems today generate a large amount of heat due to the increased demand in miniaturization and more functionality. It is estimated that out of the total electricity used for running data servers in the USA, about 50% is used to cool the systems, only 20% is used for computing while the rest is used for driving cables and communications.
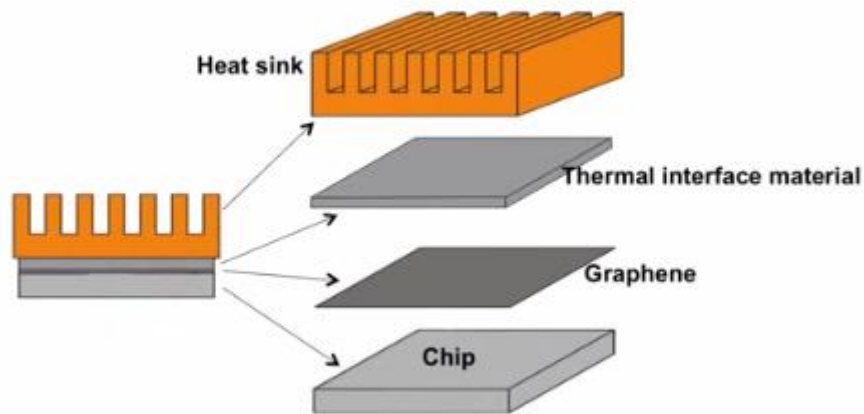
Figure 25: Use of Graphene in Thermal management

Graphene can contribute to the thermal management. It can be integrated on the chip as a lateral heat spreader. The heat is then transported to the heat sink through the so-called thermal interface material and finally dissipated into the air.

Another interesting application is the IC interconnect, because graphene is the best conductor, and also lighter and thinner than traditional materials such as copper. An additional advantage is that graphene is very stable and without electro-migration. Electro-migration is the material transport caused by the gradual movement of the ions in a conductor due to the momentum transfer between conducting electrons and diffusing metal atoms. Electro-migration is a drawback for many metal interconnects such as Cu, but not for graphene. Modern Si CMOS IC typically has multilevel interconnects.
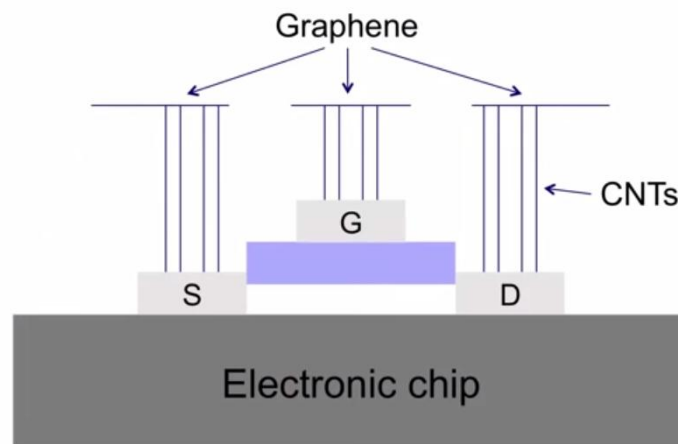
Figure 26: Use of Graphene as wire

Graphene can be used as wires within a level. Because the electrical conductivity between graphene layers is not as good as the in-plane conductivity, other materials such as carbon nano-tubes can be used to connect the graphene wires between neighbouring levels.

4.5.3) ENERGY APPLICATIONS

Due to its extremely high surface area to mass ratio, one potential application of Graphene is in the conductive plates of Supercapacitors. A supercapacitor is also called an electric double layer capacitor. Unlike traditional capacitors that have two conducting plates separated by a dielectric, a supercapacitor does not have a dielectric layer and it stores charge based on electrochemical principles.
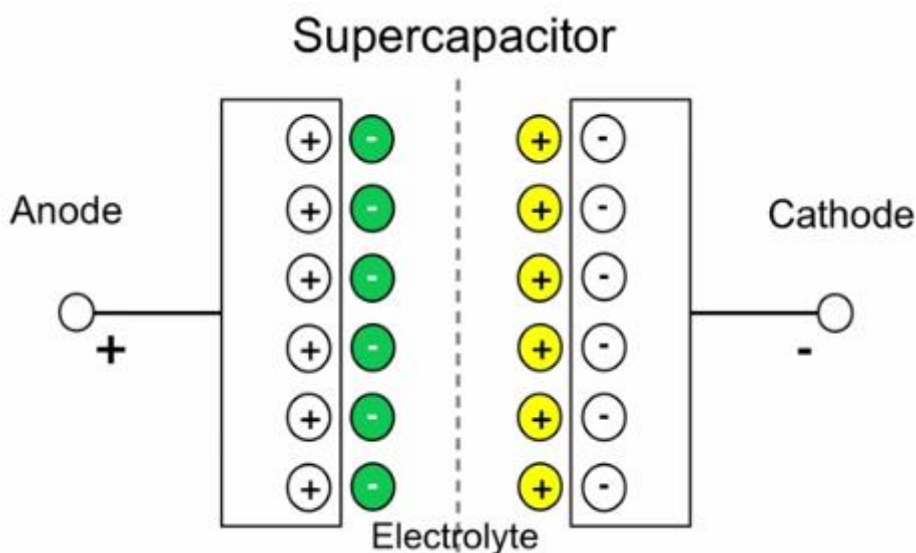
Figure 27: Schematic of Graphene based Supercapacitor

In a bath of electrolyte, two graphene electrodes (they are anode and cathode) are separated by a thin film separator. When an electric field is applied to charge the supercapacitor, anions and cations of the electrolyte accumulate at the vicinity of the graphene surface, forming electric double layer. The ions are electrically isolated from the carbon material by the electric double layer that is serving as a molecular dielectric. So the supercapacitor can be regarded as two individual capacitors connected in series. After the charging, the charges are kept stable by the electrostatic forces between the electrode and the ions in the vicinity of the electrode. Supercapacitors bridge the gap between conventional capacitors and rechargeable batteries in terms of energy density. It stores more energy per unit volume or mass which is called the energy density among all types of capacitors. The capacitance value of a supercapacitor can be up to around 1000 F which is many orders of magnitude higher than ordinary capacitors. It has a long life time and can be charged and

discharged quickly. In order to store more energy, the electrodes should have surface areas as large as possible at a given volume or mass. Obviously graphene is an ideal candidate because it is the thinnest material which leads to a super high specific surface area of 2630 m^2/g. An obvious advantage of graphene over activated carbon in supercapacitor applications is that graphene is electrically about 10 to 100 times more conducting. Nowadays supercapacitors with graphene based electrodes have a energy density approaching 60 watt-hours per litre, roughly 10 times larger than existing supercapacitors.

Finally, again because graphene is very conducting and has a large specific surface area, it can be used as the electrode material in lithium ion batteries.

Hydrogen, which is another type of important energy source, can attach to the graphene surface, rendering the graphene a nice hydrogen storage media. It has been estimated that monolayer graphene can provide a hydrogen storage weight ratio up to 7.7 wt %, which would meet the requirement for hydrogen vehicles.

4.5.4) SENSORS, ACTUATORS AND COMPOSITES

Because graphene is mechanically strong and electrically conducting, so it is suitable for nano-scale sensors and actuators (sometimes also called Nano Electro Mechanical Systems, NEMS). Sensors represent an important part of modern electronics like there are all kinds of sensors in our cell phones.
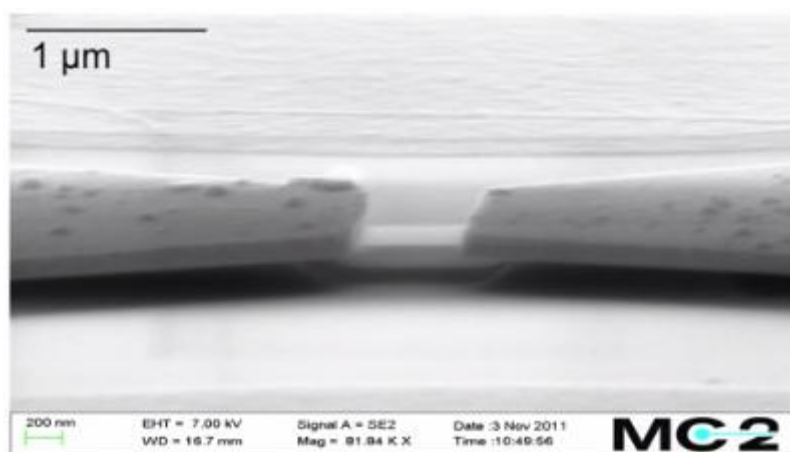

Figure 28: Graphene based Mass Sensor

It contains a suspended piece of graphene looking like a bridge on two metallic pillars. This type of device is like a transistor, and the channel can vibrate at a certain frequency if applying an oscillating signal to the gate which is the substrate in this image. If molecules are attached to the

graphene, the vibration frequency will change and by measuring this change we can determine the mass of the particle. Theory shows that the thinner the membrane the more sensitive the mass sensor is. For graphene which is the thinnest possible material, the sensor should be able to detect single molecules. Even though there are still some obstacles that need to be solved such as the quality factor of the vibrating membrane, the measurement techniques to be more mature, etc., this field is developing rapidly.

The strength of graphene makes it an interesting material that can be added to others to form composite materials. For example, adding graphene to epoxy composites may result in stronger/stiffer components. Because graphene based materials have the advantage of higher strength to weight ratio, it could find its usefulness in aviation industry. Graphene based composite materials could maybe be used to fabricate a space elevator. A space elevator is a proposed space transportation system and its main component is a long cable anchored to the surface of earth and extending into space. It permits vehicle transport along the cable from earth directly into space without the use of large rockets. Therefore, one end of this cable should be attached to the surface of earth near the equator and the other end in space beyond geostationary orbit height (about 36000 km altitude). The centrifugal effect results in the cable being held up under tension and it is kept stationary with respect to the earth. Keeping graphene's high strength and high conductivity in mind, the ambitious space elevator is maybe not just a dream!!!!

4.5.5) BIO-APPLICATIONS

One of the applications of Graphene can be DNA sequencing. To detect the sequence of DNA molecules, it typically requires several days. Graphene may offer a cheap and quick method for DNA sequencing. DNA molecules and a graphene membrane are placed in liquid containing ions. Nano-meter scale holes are prepared in the graphene, and the ions pass through the holes driven by an electric field, forming an ionic current. DNA chains also carry charges and therefore they are forced to migrate with the electric field. When they drift through the nano-holes in graphene, depending on which type of base pair is in the hole, it blocks the ionic current differently. Therefore, by measuring the change in the ionic current with respect to time, we will know the sequence of the base pairs in the DNA.

Another bio-application could be drug delivery. The reason why graphene is useful in this area is of course because it has a large surface area which can be chemically functionalized. So, it should have a good performance in drug loading. But apart from this, there is another advantage. Graphene is lipophilic. We know that our cell membrane is made of lipid bilayers. The fact that graphene is

lipophilic means it can easily penetrate into the interior of the living cells. This makes the delivery even more efficient since the drug molecules can be directly sent inside the cells. Of course, scientists have to first overcome all the safety and clinical hurdles and therefore it is reasonable to assume that graphene drug delivery will not appear until after 2030.

4.6) COMPARISON WITH OTHER MATERIALS

Material	Abundance	Ranking
Silicon (Si)	277,100	2
Phosphorus (P)	1,000	11
Carbon	480	15
Gallium (Ga)	18	35
Germanium Ge	1.8	53
Arsenic (As)	1.5	55
Indium (In)	0.049	68

Table2: Semiconductor Availability on Earth

Though silicon is abundantly available on earth yet it has an issue while shifting to nanotechnologies.

In today's complementary metal–oxide–semiconductor (CMOS) digital integrated circuits, silicon is used near 100%. Now with the geometries of MOSFET shrinking further down the 14/10 nm, the performance of silicon as MOSFET channel material is questionable, with limitations in frequency of switching, and even the switch itself is erroneously operating. Well the future can be called post-silicon era, where the industry is moving from microelectronics to nano-electronics/photonics.

(latest Si chips) increasingly small dimensions, now reaching the nano-scale, will prohibit any gains in performance due to the nature of Silicon and the laws of physics. Within a few more generations, classical scaling and shrinkage will no longer yield the sizable benefits of lower power, lower cost and higher speed processors that the industry has become accustomed to."

In the immediate future, the transition into <7nm is basically moving into non-Silicon CMOS switching, EUV lithography and increased on-chip photonics, a combination of control of electrons and photon flow in single integrated device. The 3D growth of structures will be more prominent.

Graphene can be the replacement to Silicon because of its amazing properties but breaks easily during manufacturing so other devices are conferred during silicon manufacturing techniques.

Going by the Formulas,

μn (Graphene) = 2×10^5 cm^2/Vs μn (GaAs) = 8500cm^2/Vs μn (Ge) = 3900 cm^2/Vs

μn (Si) = 1450 cm^2/Vs   μn (GaN) = 1000 cm^2/Vs

Because μn (Graphene)>μn (GaAs)>μn (Ge)>μn (Si)>μn (GaN), so theoretically,

Id (Graphene)>Id (GaAs)>Id (Ge)>Id (Si)>Id (GaN),

gm (Graphene)>gm (GaAs)>gm (Ge)>gm (Si)>gm (GaN)

g_0 (GaAs)>g_0 (Ge)> g_0 (Si)> g_0 (GaN)

Other material which is better than graphene is MoS_2, is a very effective semiconductor. This mineral, which is abundant in nature, is often used as an element in steel alloys or as an additive in lubricants. But it had not yet been extensively studied for use in electronics. Band energy is 100,000 times less. It's a two-dimensional material, very thin and easy to use in nanotechnology. It is better than graphene in a way that in solid-state physics, band theory is a way of representing the energy of electrons in a given material. In semi-conductors, electron-free spaces exist between these bands, the so-called "band gaps." If the gap is not too small or too large, certain electrons can hop across the gap. It thus offers a greater level of control over the electrical behaviour of the material, which can be turned on and off easily.

The existence of this gap in molybdenite also gives it an advantage over graphene. Considered today by many scientists as the electronics material of the future, the "semi-metal" graphene doesn't have a gap, and it is very difficult to artificially reproduce one in the material.

5) RESULTS

5.1) TRANSFER CHARACTERISTICS

Id vs Vg plot (with varying Vd).
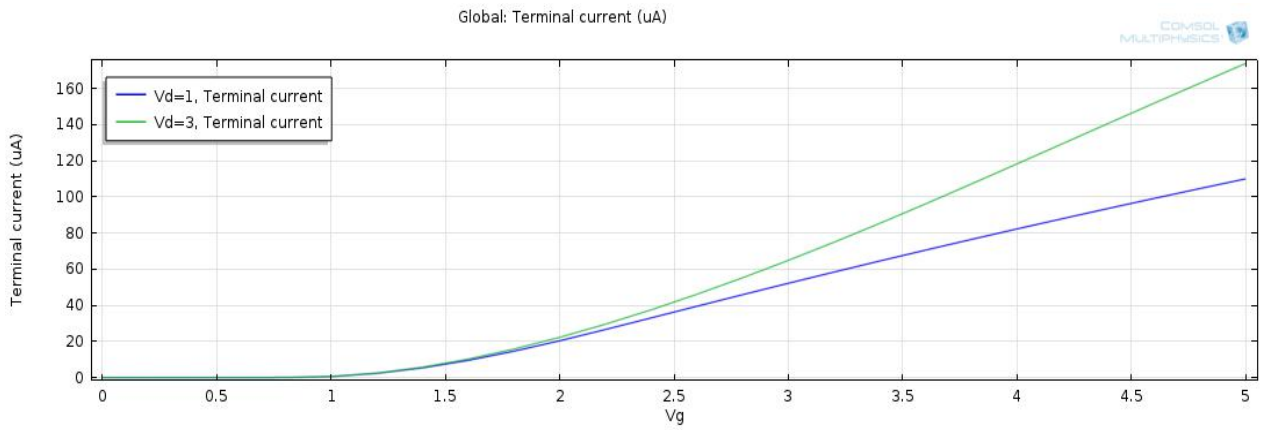
Figure 29: Silicon
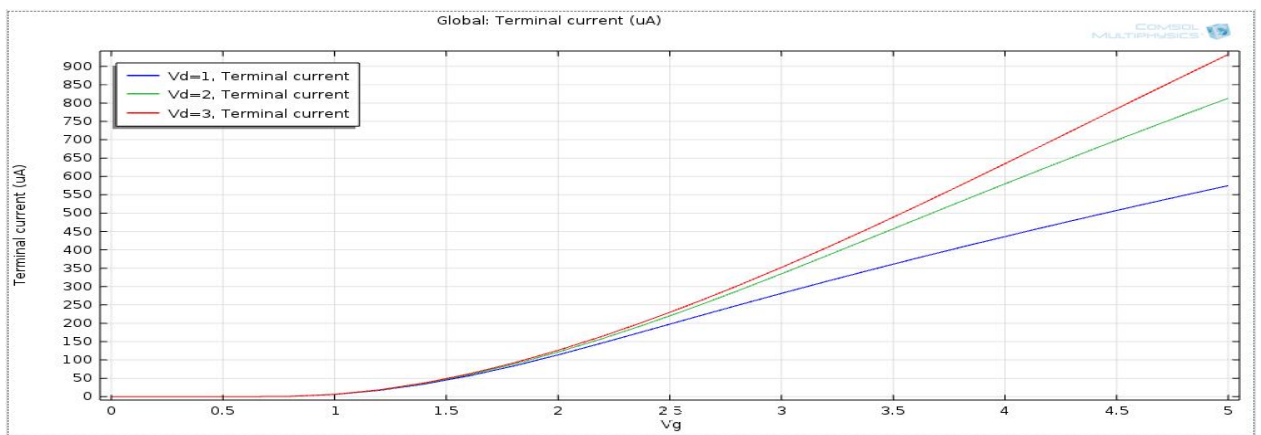
Figure 30: Germanium
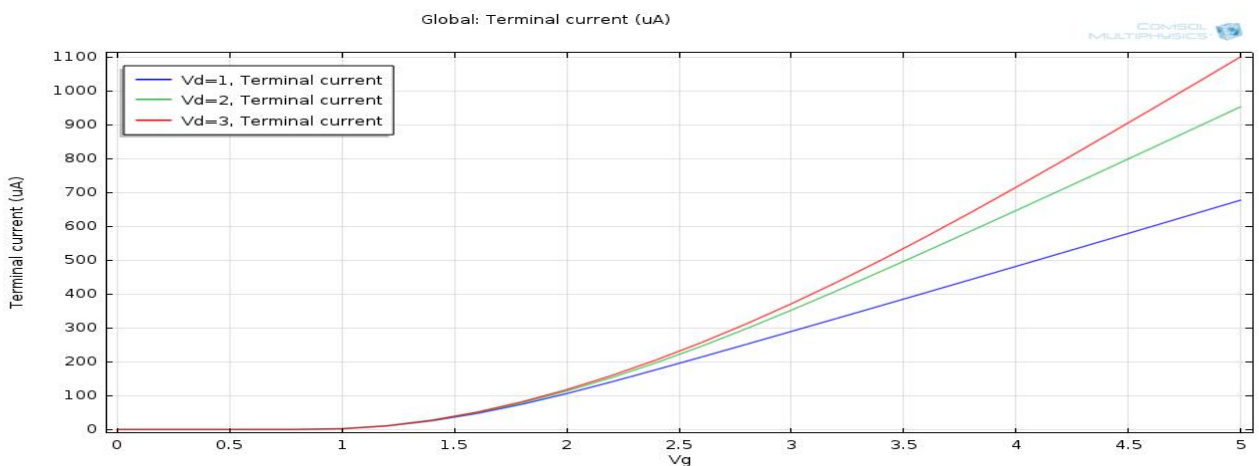

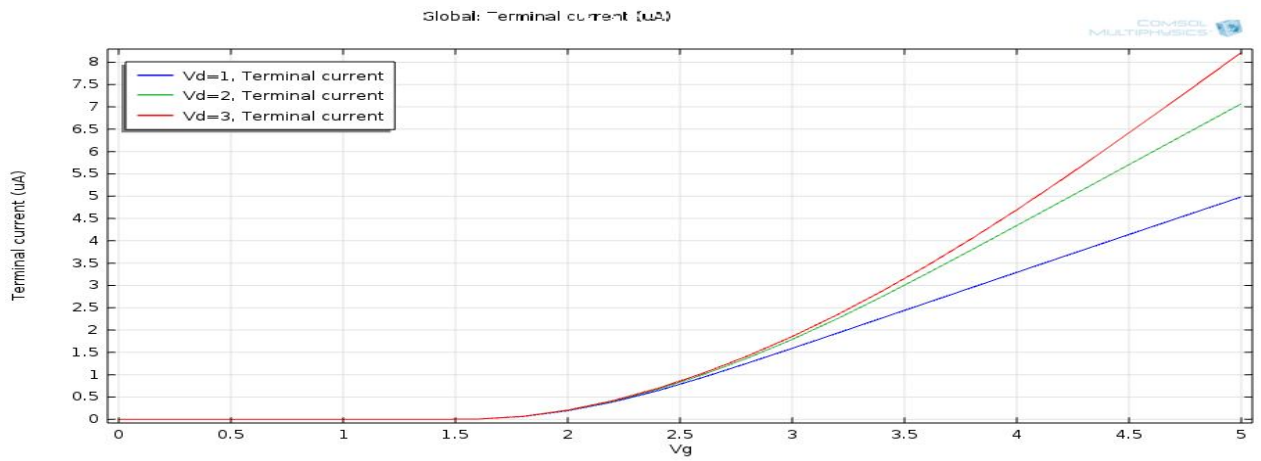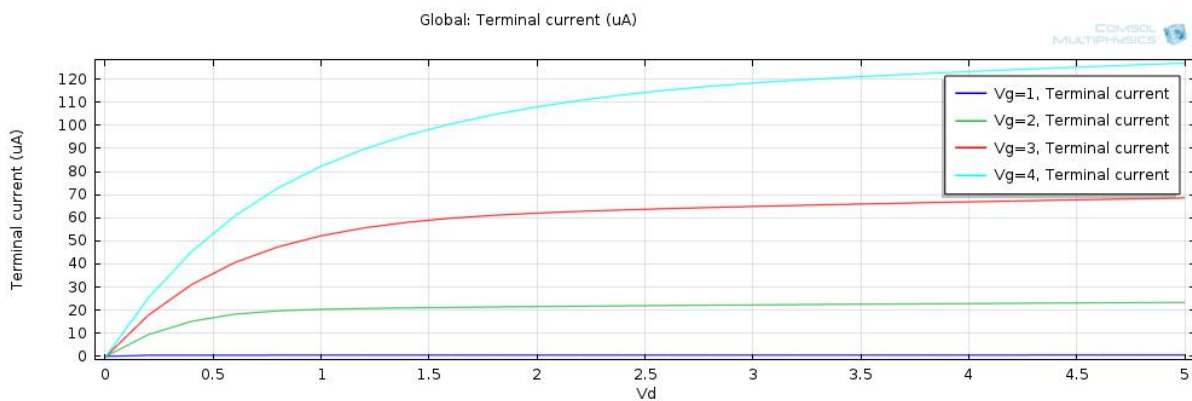Figure 31: Gallium Arsenide.

Figure 32: Gallium Nitride

INFERENCE:

Vt(GaN)=1.45V   ni(GaN)=1.9*10^(-4)/m^3

Vt(GaAs)=0.85V   ni(GaAs)=1.8*10^(12)/m^3

Vt(Si)=0.8V   ni(Si)=1.45*10^(16)/m^3

Vt(Ge)=0.6V   ni(Ge)=2.4*10^(19)/m^3

Therefore, Vt(GaN)>Vt(GaAs)>Vt(Si)>Vt(Ge)

Because ni(GaN)<ni(GaAs)<ni(Si)<ni(Ge) hence threshold voltage is inversely dependent on intrinsic concentration.

Also, threshold voltage is dependent on relative permittivity of the substrate. But the effect of intrinsic concentration is greater than that of threshold voltage.

Vt is independent of Vds(or Vd).

The above inferences have been complied on the basis of following equations:

$$V_T = \Phi_{GC} - 2\phi_F - \frac{Q_B}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}$$

41

Where,

$$\phi_F(substrate) = \frac{kT}{q} \ln\left(\frac{n_i}{N_A}\right)$$

And

$$Q_B = -\sqrt{2q \cdot N_A \cdot \varepsilon_{Si} \cdot \left|-2\phi_F + V_{SB}\right|}$$

5.2) DRAIN CHARACTERISTICS

Id vs Vd plot (with varying Vg).
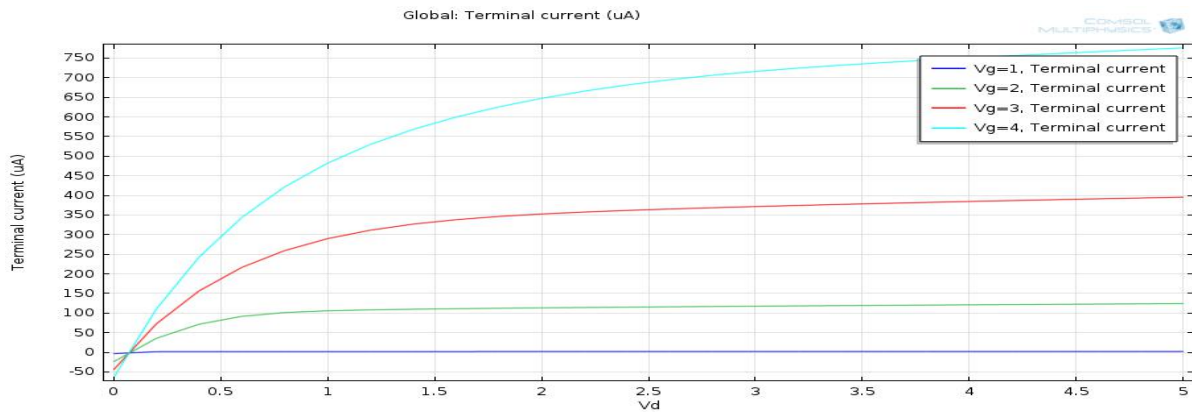

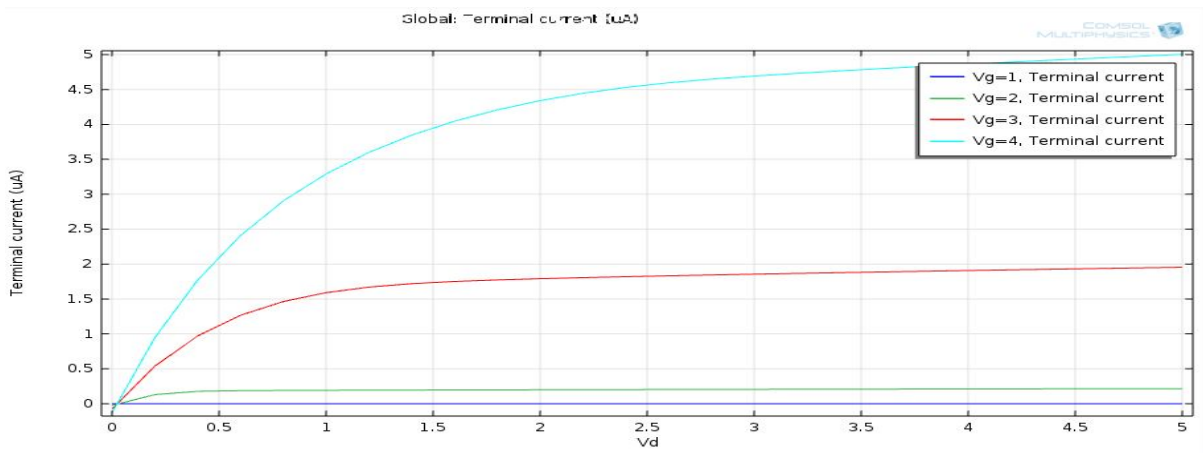Figure 33: Silicon
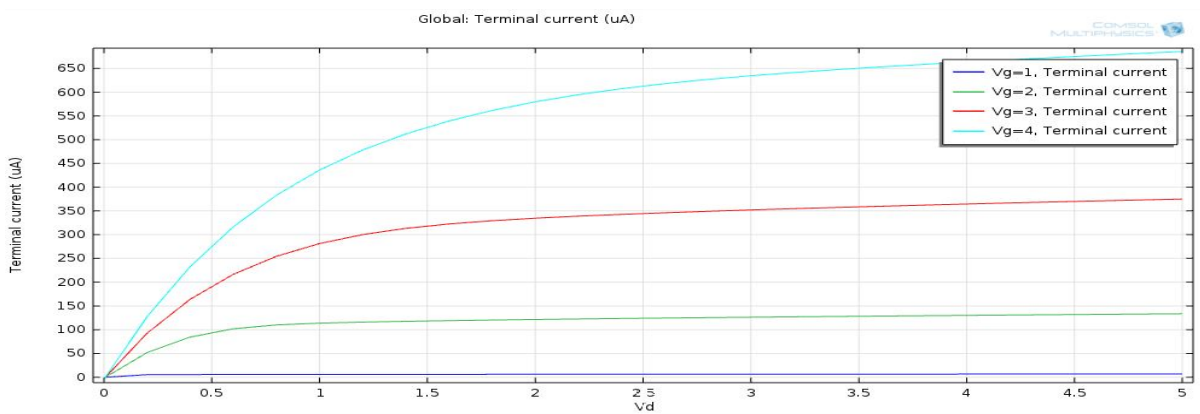
Figure 34: Germanium

Figure 35: Gallium Arsenide

Figure 36: Gallium Nitride

INFERENCE:

Id(GaAs)=800uA   µn(GaAs)=8500cm^2/Vs

Id(Ge)=700uA   µn(Ge)=3900 cm^2/Vs

Id(Si)=130uA   µn(Si)=1450 cm^2/Vs

Id(GaN)=5uA   µn(GaN)=1000 cm^2/Vs

Therefore, Id(GaAs)>Id(Ge)>Id(Si)>Id(GaN)

Because µn(GaAs)>µn(Ge)>µn(Si)> µn(GaN). Hence, drain current is directly proportional to the electron mobility.

Also, drain current is dependent on threshold voltage. But the effect of electron mobility is greater than that of threshold voltage.

At constant gate to source voltage, drain current increases with the increase in drain to source voltage.

At constant drain to source voltage, drain current increases with the increase in gate to source voltage.

The above inferences have been complied on the basis of following equations:

$$I_D = \mu C_{ox} \frac{W}{L}[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}], \quad \text{for } V_{DS} < V_{GS} - V_T$$

And
$$I_{D,sat} = \mu C_{ox} \frac{W}{L} \frac{(V_{GS} - V_T)^2}{2}, \quad \text{for } V_{DS} > V_{GS} - V_T$$

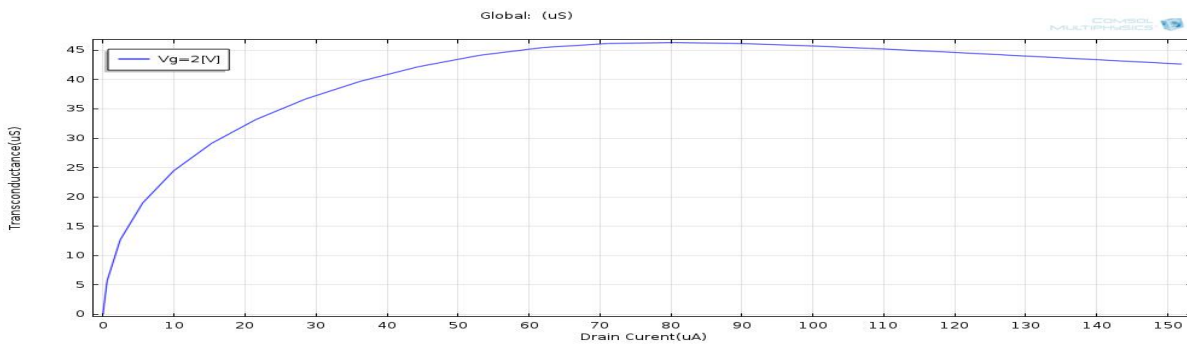## 5.3) TRANS-CONDUCTANCE

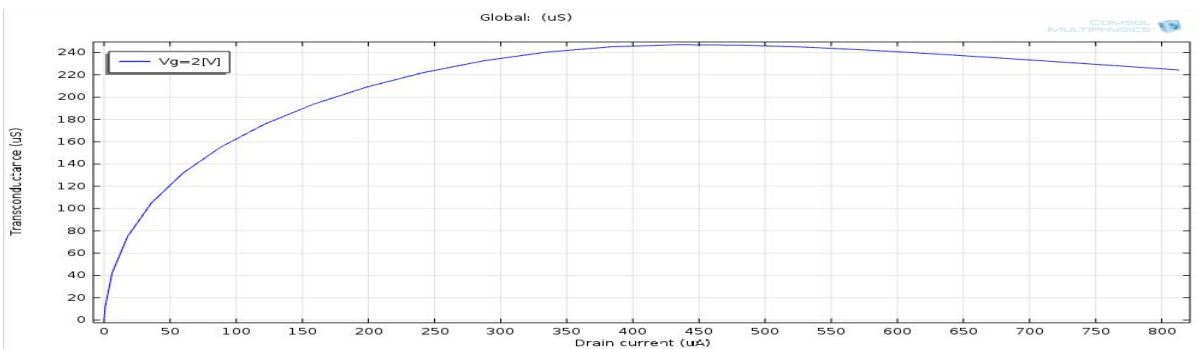gm vs Id plot (with constant Vd).

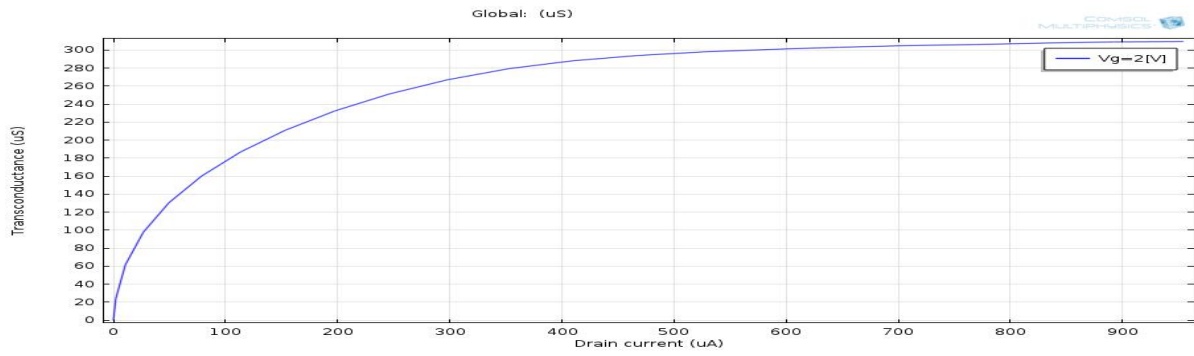Figure 37: Silicon
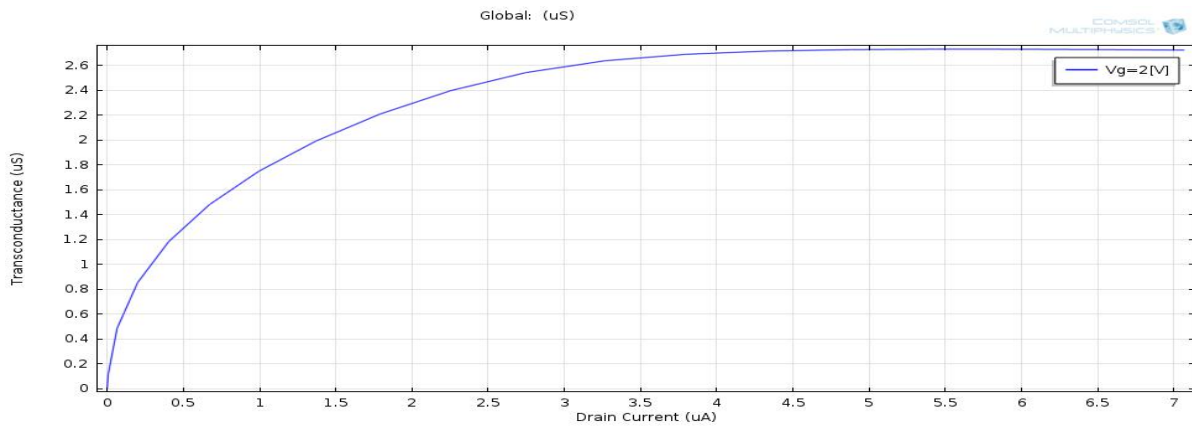

Figure 38: Germanium

44

Figure 39: Gallium Arsenide.

Figure 40: Gallium Nitride

INFERENCE:

gm(GaAs)=300uS   µn(GaAs)=8500cm^2/Vs

gm(Ge)=240uS   µn(Ge)=3900 cm^2/Vs

gm(Si)=45uS   µn(Si)=1450 cm^2/Vs

gm(GaN)=2.8uS   µn(GaN)=1000 cm^2/Vs

Therefore, gm(GaAs)>gm(Ge)>gm(Si)>gm(GaN)

Because µn(GaAs)>µn(Ge)>µn(Si)> µn(GaN). Hence, trans-conductance is directly proportional to the electron mobility.

The above inferences have been complied on the basis of following equations:

$$g_m \overset{\Delta}{=} \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}$$

45

The trans-conductance in the quadratic region is given by:

$$g_{m,quad} = \mu C_{ox} \frac{W}{L} V_{DS}$$

which is proportional to the drain-source voltage for $V_{DS} < V_{GS} - V_T$. In saturation, the trans-conductance is constant and equals:

$$g_{m,sat} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T)$$

5.4) OUTPUT CONDUCTANCE

g0 vs **Id** plot (with constant Vg).
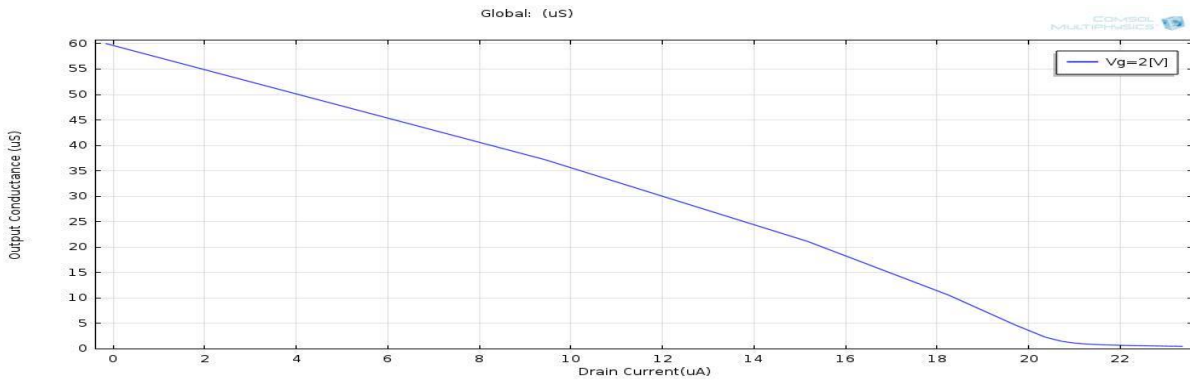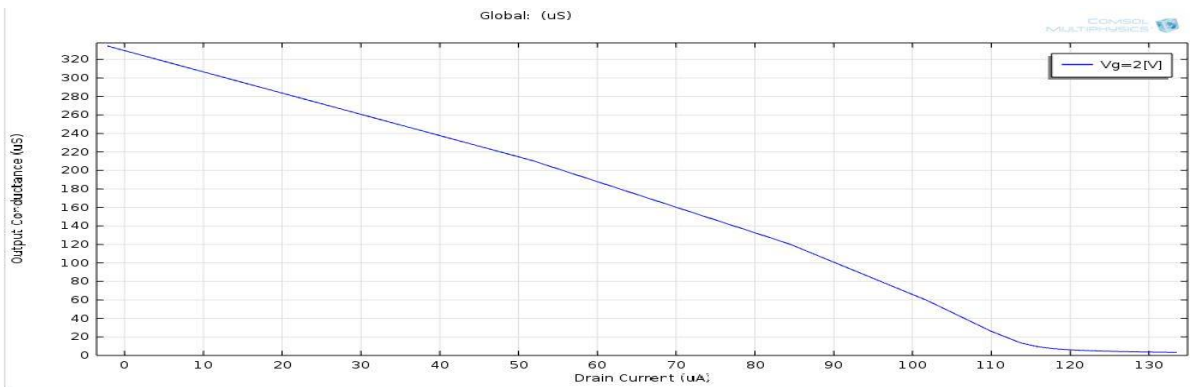

Figure 41: Silicon

Figure 42: Germanium
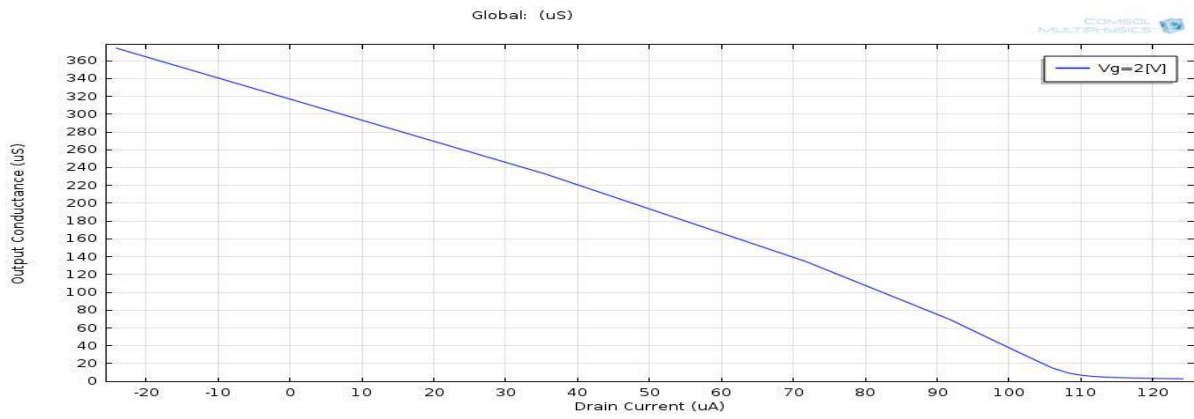
Figure 43: Gallium Arsenide.
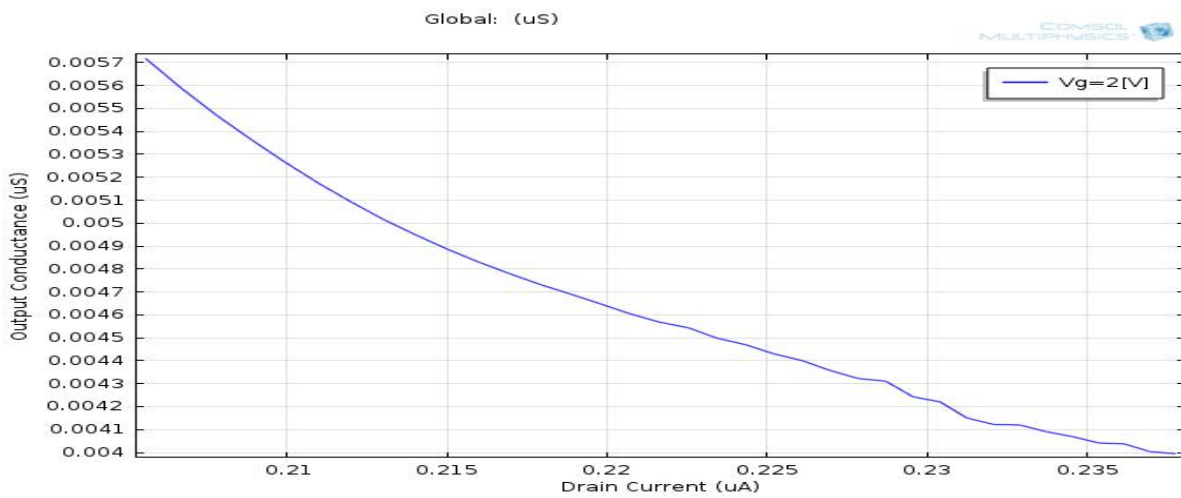
Figure 44: Gallium Nitride

INFERENCE:

g0(GaAs)=379uS   µn(GaAs)=8500 cm^2/Vs

g0(Ge)=340uS   µn(Ge)=3900 cm^2/Vs

g0(Si)=60uS   µn(Si)=1450cm^2/Vs

g0(GaN)=0.057uS   µn(GaN)=1000 cm^2/Vs

Therefore, g0(GaAs)>g0(Ge)>g0(Si)>g0(GaN)

Because µn(GaAs)>µn(Ge)>µn(Si)> µn(GaN). Hence, trans-conductance is directly proportional to the electron mobility.

The above inferences have been complied on the basis of following equations:

$$g_d \overset{\triangle}{=} \left. \frac{\partial I_D}{\partial V_{DS}} \right|_{V_{GS}}$$

The output conductance in the quadratic region decreases with increasing drain-source voltage:

$$g_{d,quad} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T - V_{DS})$$

and becomes zero as the device is operated in the saturated region:

$$g_{d,sat} = 0$$

Gallium Arsenide MOSFET is favourable for the present technology where the number of MOSFETs on a single chip is less as compared to the future technology as its current rating is more as compared to Silicon and Germanium.

Gallium Nitride MOSFET is favourable for the devices where the number of MOSFETs required on a single chip is very large. Its current ratings are very less, so, the dissipation of heat for a single MOSFET reduces significantly. Also, Gallium Nitride for better in the age of miniaturization. As the size of MOSFET is decreasing, the conventional Silicon MOSFET has the power dissipation as the major issue. So, Gallium Nitride is much more favourable.

$$g_d \overset{\triangle}{=} \left. \frac{\partial I_D}{\partial V_{DS}} \right|_{V_{GS}}$$

6) CHALLENGES

Transistor scaling has been the driving force for technology advancements in the semiconductor industry over the last few decades. In order to mitigate short channel effects, the gate-oxide thickness and source/drain junction depth have been scaled along with the gate length. Also, new semiconductor materials have come in existence; following are some challenges that have to be overcome with the advancement of the technology:

- Germanium, Gallium Arsenide and Gallium Nitride crystals are costlier than Silicon which makes the manufacturing and production cost of MOSFET higher.
- The large dielectric constant of the Ge substrate makes devices prone to the short channel effect (SCE). Here, the gate terminal cannot turn off the device, since the drain and source terminals couple strongly through the substrate because of its high permittivity, and transistor action is no longer observed.
- GaAs is extremely brittle. For this reason, GaAs wafers are typically smaller than three inches in diameter, as opposed to silicon wafers, which commonly have diameters of eight or more inches. Since the area on a wafer is proportional to the square of its diameter, Si has a huge cost advantage over GaAs.
- It is difficult to fabricate MOSFET in III-V materials as surface passivation constitutes a severe technical issue for all III-V materials.
- No high-quality insulators (counterparts to silicon dioxide) grow on GaAs.
- The insulator/GaAs interfaces have high levels of defects called "traps" that make GaAs MOSFET's impossible. This is probably the main reason that GaAs will never supplant Si as the semiconductor-of-choice for integrated circuits till date.
- GaAs transistors are usually either MESFET's or HEMT's. These transistors have some advantages over MOSFET's but their disadvantages outweigh the advantages.
- The epitaxial growth of GaN on the silicon wafer makes the manufacturing of the GaN MOSFETs costlier.
- The hole mobility in GaAs is 15-20 times smaller than the electron mobility, which makes CMOS-like circuits unattractive.
- Due to the arsenic that GaAs contains, it is poisonous and dangerous to work with and to manufacture.
- As the dimensions of MOSFETs are scaled down, the contact resistance of silicide-to-source/drain regions increasingly limits transistor performance. This is because the on-state

resistance of a MOSFET drops with transistor scaling, whereas contact resistance increases with contact area scaling.

- GaN MOSFETs have a high off state leakage current and the MOSFET is normally on.
- In GaN MOSFET, the gate oxide reliability is limited to 250ºC or less

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