



# Two Dimensional Electron Gas (2DEG) Systems

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**Abstract-** The present text gives a brief outline of the electronic properties of semiconductor structures where the carrier motion is strictly confined along one of the coordinates to a very narrow region of not more than a few hundred Nano. If this width is comparable with the de Broglie wavelength of the carriers, then an entirely new class of physical phenomena, called quantum size effects, appears. These phenomena drastically alter most electronic properties of the system and can be applied to a series of principally new electron devices. Also check the examples which have two-dimensional electron gas structure and in some cases partly explains the differences between them. In some section, the properties of which will be cited by the authors.

**Keywords-** 2DEG, Quantum Hall effect, MOSFET, Graphene, Heterostructure

## I. INTRODUCTION

In 1879 One interesting phenomenon in magnetic has been discovered by EDWIN HERBERT HALL [1] and it is called HALL EFFECT.

This effect is generated from the motion of the charged particle in two electric and magnetic fields that has various usages in electronic components, and modern solid state physics [2], and in labs in order to determine the characteristics of semiconductors and specially the density of charge carriers (free electron). In 1980 a new effect discovered, in HALL's experiments that opened a new season in physic principles .In the same year Klaus von Klitzing [3] from Max Planck institute of Stuttgart in West Germany with his partners J. Dorda from Siemens, Munich and M. Pier from Cavendish Cambridge England [4] , reported that in their studying in a determined circumstance , Hall resistance changes curve ( $R_H$  hall's voltage / current I),is in the form of step function and the value of the On State is unbelievably stable and doesn't depend on its material type , its geometrical shape ,etc....

With a very accurate view ,they are just function s of two fundamental constants of physics , Plank constant h and e electric charge .And they change as integer divisions of one fundamental quantum unit  $h/e^2$  (negative integers). $R_H$  is quantum like equation(1):

$$R_H = h/ie^2 \quad i=1,2,3,\dots \quad (1)$$

As one of the possible application the Hall resistance of the periodically modulated two-dimensional electron system in the strong magnetic field is briefly discussed in [5]

Quantum Hall effect is a pure experimental discovery and is visible under circumstances that in comparison with classical Hall effect is unusual .It means in measurement , very powerful magnetic field ( $T10 < B$ ) , and temperature of 0 Kelvin( $T< 4k$ ) is required .The sample used in this experiment (MOSFETS &...)includes Two-dimensional electron gas (2DEG).2DEG is a set of electrons that are covered in a thin layer (8 n) near to the common part between two differenet materials .The structures of 2DEG have some exclusive Properties that are not visible in a system of electrons and 3D holes. Such structure can be used in devices that are made from semiconductors, specially Electro-optical devices .the reason why 2DEG structures are interesting, mostly lays in the Molecular Beam Epitaxy (MBE) technology, that is the most suitable technology for such structures with profile and with an accuracy of a single layer. And the role of Molecular Beam Epitaxy (MBE) in recent discoveries of the quantum Hall effect discussed in [6] .A series of properties of these systems can be found in [7-20].

## II. MOSFET (METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTOR)

The first sample used on 2D systems was a very well made transistor called MOSFET.[4]

In MOSFETs the density of charge carriers can be changed with a help from one electric field. And this is the main difference between MOSFET structure and other quantum size systems.

The density of surface electron in inversion layer can be calculated from equation (2).

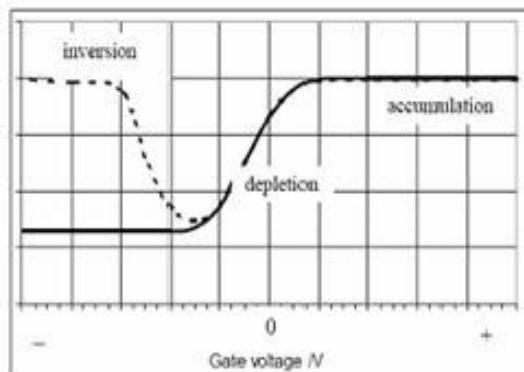
It's proportional to  $V_g$ .

$$n_s = \epsilon_d (V_g - V_0) / 4\pi e d \quad (2)$$

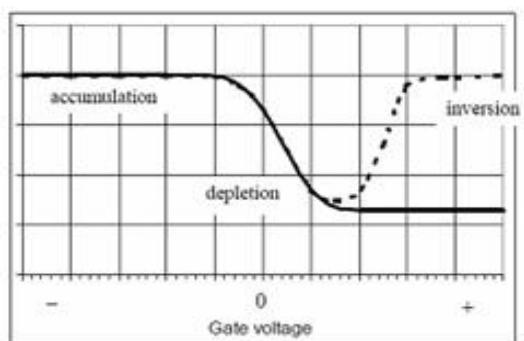
In this formula  $d$  and  $\epsilon_d$  are thickness and dielectric constant .and also  $V_0$  is threshold voltage for opening the channel in order to emerge electron .the first MOSFET sample was silicon MOSFET, not only is a fundamental component in microelectronics [21,22] but also has very important usages in solid state physics [23-25]. Also MOSFETs have recently

been proposed for use in radiation therapy[26]. The main usage of these transistors is measuring Hall Effect.

The body of this cuboid transistor is tenth of millimeter wide, and few millimeters long. Its case is usually made from P or N type silicon(c-v curve for N and P semiconductors is shown in fig .1) that one thin layer of silicon oxide with a thickness between 30 Nano to 150 Nano is developed on its surface.



The C-V characteristics for N type semiconductors



The C-V characteristics for P type semiconductors

Figure 1. C-V characteristics for P & N type semiconductors.

Two zones that huge amount of n+ is injected into them, are SOURCE and DRAIN that are made by Ion implantation or other methods and used as links between current and potential probes .One conductor layer called GATE with a metal or multi injected silicon on its oxide surface form one parallel plate capacitor.(fig 2)

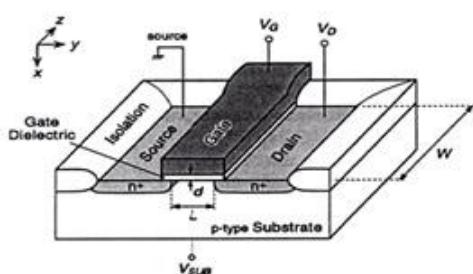


Figure 2. MOSFET

Applying a voltage to the gate that is positive relatively to the body would hold back the holes from the edge of connection si-sio<sub>2</sub> and instead, it would absorb one layer of electrons to the common part. This electron layer is called inversion layer. Because, In fact with applying voltage to the gate, We have reversed the majority carriers in the silicon common part (the density of inversion layers carriers In silicon MOSFET is compatible to the gate voltage, and is another property for MOSFETS); Now the inversion layer is the one of the conductive plates and gate metals is another part of capacitor's conductive plates. Thus inversion layer has a small resistance, by applying voltage between source and drain, electric current will flow between these two.

As we said, inversion layer is extraordinarily thin and its thickness at maximum doesn't reach to 8 nano, so charge carriers are settled in a very thin and common zone of two materials and just can move in (x-y) surface, thus by applying electric field to the oxide layers, the edge of silicon conduction band will bend down and charge carriers will absorb to the common part.

So these electrons are settled in an almost rectangular thin well with a thickness of 8 nano (fig 3) (In fact its figure is more complicated, and its shape is determined by electric charge and electric field) and specially their movements in low temperature are 2D, and are called 2DEG.

Energy balances [27] in such triangle well are achieved from equation (3)

$$E_N = \left( \frac{h^2}{2m} \right)^{\frac{1}{3}} \left[ \frac{3\pi eF}{2} \left( N - \frac{1}{4} \right) \right]^{\frac{2}{3}} \quad (3)$$

$$\text{And } F = 4\pi e n_s / \epsilon .$$

F is the field near common part and it is proportional to Vg,  $\epsilon$  is semiconductor's dielectric permittivity.

The characteristic width of the channel  $Z\Delta$  can be estimated.

If we define  $Z\Delta$  as classic valid width range for electrons with  $E_N$  energy so from equation (4):

$$\Delta Z = E_N / eF \quad (4)$$

$$\Delta Z \approx F^{-\frac{1}{3}}, \text{ so } Vg \text{ will decrease.}$$

Based on last equation, it seems that 2DEG is found in other potential wells .And its existence for the first time was reported by Feng and Howard [28], by experiments. And in 1957 Scheriffer [29] reported that if it is possible to generate an inversion layer, the behavior of the electrons that settled in this thin potential well Would not be classical , and they would have quantum energy .

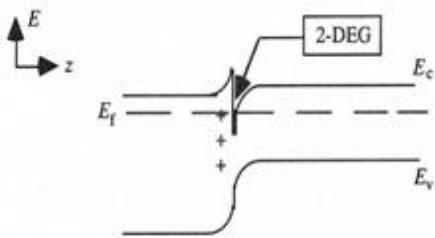


Figure 3. Two dimensional electron gas system (2DEG)

We should say that, the inversion layer (for a state that substrate is P type) is formed after four steps:

In the first step  $V_G = 0$  (Gate voltage) and the energy band is Flat Band and there is no charge layer in it.

Second step is called Accumulation that  $V_G < 0$ .

For this voltage, one electric field appears in oxide. Negative voltage will bend up silicon bands. Therefore, FERMI balance is closer to Valence band edge. So extra holes are settled on the surface of semiconductor oxide and electrons are settled on the surface of metal oxide (bottom side of figure 4 shows this subject)

Third step is called Depletion region, and it is Gate's positive voltage but it is smaller than threshold voltage  $V_T$ , this means ( $V_T > V_G > 0$ ).

In here inherent FERMI balance and real FERMI balance will meet in one common point.

For depletion region, silicon bands are bent down so by holes depletion, one substituted layer that is charged negatively appears on the surface of semiconductor oxide .the size of the depletion region is increased when  $V_G$  is increased.

In the same way, the surface region of metal-oxide is charged, that is also shown.

In fourth step, for  $V_G > V_T$  inherent FERMI balance is lower than real FERMI balance then inversion layer is formed and electrons motion is stopped.[30] And so a series of properties of these systems can be found in [7-14, 31-33].

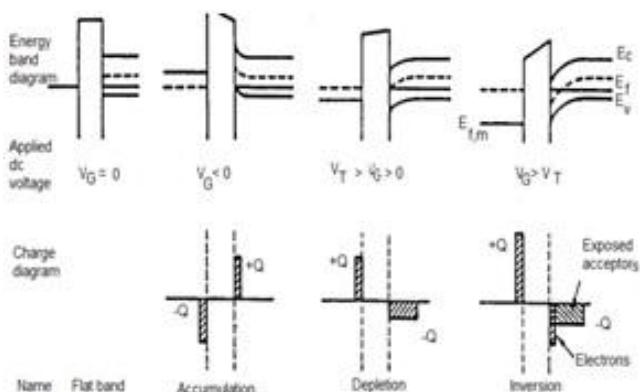


Figure 4. how inversion layer in MOSFETS is formed.

### III. THIN FILMS

Thin films are the most common structure that contains size-quantum and thus its effects must be seen, semiconductor or Semi metallic films should be used.

BI films are the first structure that can show the effect of quantum size in conductivity [34] Bi films with sufficient thickness, sufficient acceleration and high quality can easily be made with evaporation method in vacuum.

Changes in electrons centralization , simultaneously will change the distance between quantum size balances .this property separates MOSFET structure from thin layers that centralization and calculated energy balances in them , respectively are separable by Pollution levels and layers thickness.

The other difference between MOSFET and thin films is that, the thin film play the role of potential well for both charges. and energy quantization happens for both electrons and holes ,but in MOSFET structure like any other system that the bounding potential is in the form of electrostatic ,at least in one side only one type of carrier is quantized .for other type of carriers (holes)there is no potential well ,and Energy spectrum remains continuous. Also study of properties thin films exist in[11, 35,36].

### IV. GRAPHENE

One paper that had been published in SCIENCE magazine in 2004 that became very famous globally.

Graphene is one type of carbon that not only is the thinnest but also the roughest carbon .and also has better performance in conducting heat and all other parameters.

Graphene is almost transparent. Nevertheless it is that dense that even helium (smallest gas atom) can't pass through it. Also graphene is an exciting material[37] that has high Theoretical Specific Surface Area ( $m^2630^2g^{-1}$ ), high Intrinsic mobility ( $200\ 000\ cm^2v^{-1}s^{-1}$ ) [38,39] , high Young modulus ( $\sim 1.0\ TPa$ ) [40], high Thermal ( $\sim 5000\ w m^{-1}k^{-1}$ )

[41],high Optical transmittance (97.7%) [42] ,frequency about ( $1580\ cm^{-1}$ ), good electrical conductivity and also has usage in transparent conductive electrodes [43,44] and carbon nanotubes .

Graphene is obtained from ordinary carbon that is used in pencil.

Geraphene is a semi metal that its surface form is consist of only six separate dots and also it is consist of carbon atoms in a flat lattice same as beehive structure ,but they are connected with a thickness of only one atom.

Figure below shows beehive lattice of graphene .the unit cell is bounded by two  $a_1$  and  $a_2$  vectors (fig 5), and it is consist of 2 carbon atoms in  $(a_1+a_2)/3$  and  $2(a_1+a_2)/3$  that  $a_1$  and  $a_2$  basic vectors have length of  $|a_1|=|a_2|=a_0=0.264$  nano with the angle of  $60^\circ$  to each other. [45]

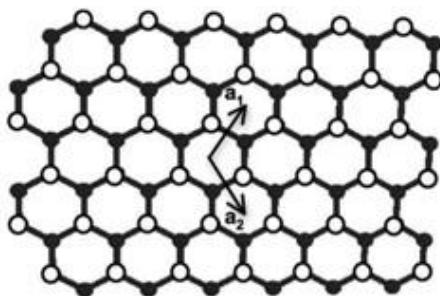


Figure 5. Graphene with  $a_1$  and  $a_2$  basic vectors.

In fact single 2D graphite layer is called graphene. It can be said that one millimeter of graphene is consist of 3 million layers. The connection between these layers is weak, so they can easily be separated. Anyone who has written with an ordinary pencil has the experience of separating these layers. By separating these layers, it is possible that one layer of graphene atoms remains on the paper .and this is the exact thing that happened when Andre Konstantin Geim and Konstantin Sergeevich regularly took some small layers of graphite from big pieces by using tapes.

At first they got some crusts that had many graphene layers, but when they used the tape method for 20 times, the crusts became thin and thinner .next step was finding the very small parts of graphene among graphite's thicker layers and carbon slivers .at this time, the scientists of Manchester university decided to connect the layers to a silicon oxide plate in order to see the results of their very accurate work. When the plate is placed under standard microscope, a rainbow of colors can be seen, like the oil that is spilled on water. Therefore the numbers of layers can be determined .the thickness of bottom silicon dioxide layer is also important in the process of revealing graphene. Under microscope, they saw graphene in the form of one 2D crystal layer at room temperature.

Therefore graphene is a quite regular carbon network with length and width dimensions .one basic unit of this design is consist of billions of carbon atoms that chemically are connected together.

graphene is consist of billions of carbon atoms that are connected together in the form of hexagonal.

One ring of graphene sheets with 70 cm width is the biggest graphene that is made up to now. The first property is the nearly perfect combination of graphene.

It's perfect regularity is due to the strict connection between carbon atoms.

And also the connections are sufficiently flexible, and can be stretched up to 20 % of its standard shape[40 , 46].also the network allows the electrons to cross long distances inside of the graphene without any disturbance.

Although graphene is a single layer of the graphite but it has other special property that is the behavior of its charge carriers. These carriers act like massless relativistic particles and they move with a speed of only 300 times slower than the speed of light .(it is faster than the movement speed inside of

the silicon).thus , graphene is called a suitable option for future replacement with silicone used in computers chips. [47]so these carriers follow massless relativistic particle equations, although there's no relativity characteristic for electrons and their motion near carbon atom. Such particles are called massless Dirac fermions, they are electrons that have lost their inertial mass, so the determining equation for graphene is the same equation that determines charged Neutrino. due to dispersion relation in geraphene, Fermi velocity of low energy electrons is independent from their energy .therefore graphene is semimetal without energy gap, that its band structure in Brillouin zone is in the form of cone and they cut each other in Dirac zone[48].(fig6)

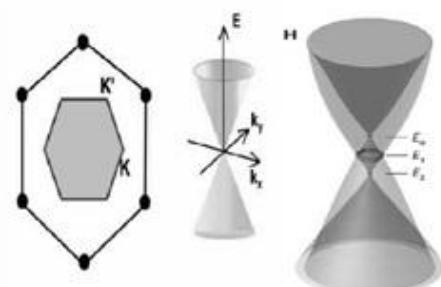


Figure 6. Graphene is semimetal without energy gap, that its band structure in Brillouin zone is in the form of cone and they cut each other in Dirac zone.

Based on tight binding theory only the first closest neighbor's interaction provides electron depression relation near  $k'/k$  points same equation (5): [49, 50]

$$E_{\pm}(\vec{k}) = \pm \sqrt{1 + 4 \cos \frac{\sqrt{3}k_x a}{2} \cos \frac{k_y a}{2} + 4 \cos^2 \frac{k_y a}{2}} \quad (5)$$

In a place that  $a = \sqrt{3} a_{cc}$  and  $a_{cc}$  is the length of carbon-carbon junction (0.142 nm) and  $t$  is the total energy transfer and also the closest neighbor to the 2.8ev.

Negative sign shows the valance band ( $\pi$ ) of geraphene that is completely occupied .and positive sign shows conduction band ( $\pi^*$ ) that is empty.

With above equation, near  $k'/k$  points, depression can be determined by this equation  $E_{\pm}(\vec{q}) \approx \hbar v_f |\vec{q}|$  , that  $\vec{q}$  is the measured momentum dependent to dirac point.

$\hbar = h/2\pi$  where  $h$  is the Planck's constant and  $v_f$  is Fermi velocity  $v_f = \sqrt{3}ta/2$  with a value about  $1 \times 10^6 \text{ ms}^{-1}$  .

Linear band structure is precisely similar to Dirac spectrum for massless fermions. [37]electronic states near Dirac points are different from sub lattice s states ,sub lattices portions are recognizable by using two wave function components. Therefore Hamilton effect near to  $k'/k$  points with zero mass can be stated like equation (6):

$$\hat{h} = \hbar v_f \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} \quad (6)$$

In a place that  $\vec{k}$  is Quasi particles momentum in graphene and  $\vec{\sigma}$  is 2D Pauli matrix .two describing components of graphene, are similar to Spinor wave function in quantum electrodynamics (QED), but spin index for graphene points to sub network instead of pointing to real electron's spin. And usually are referred as pseudo spin.

Experimental observation interprets Dependence of cyclotron mass to square root of the electronic density in graphene as a sign for the existence of Dirac massless pseudo spins in graphene.[51, 52]

Quantum Hall effect in metalloid systems that electrons are bounded in them.only happens when they move in a 2 D plate. This effect is known by making sudden flat parts in a conduction diagram that is plotted based on current flow in the plotted system. This conduction is called Hall conduction. Constantly this part is made after applying a powerful electromagnetic field to the plate.

Hall's quantum effect in graphene is a little bit different from other 2Ds systems , usually Hall's conductivity starts from zero and increases by enhancement of magnetic field or charge compression in an exact and precise value (called  $e^2/h$ ) .in graphene ,change in conductivity is a multiple of  $4e^2/h$ .

And all characteristics will be changed to half of this value. Moreover in most systems Hall conductivity usually is terminated by dislocation or vibrations in very higher temperature than absolute zero temperature; but in graphene Hall conductivity significantly is independent from these two factors, and flat parts of Hall conductivity around absolute zero are remained unchanged by the enhancement of temperature to room temperature. Therefore one group of international physicists like Akira Furusaki from Institute of Advanced Science are trying to discuss the unusual Hall quantum effect seen in graphene, by doing a numerical studying .the investigation about the effect of the existing dislocations in 2D structure of graphene, on the behavior of this material has been one of the other goals of this investigation.

Their simulations indicate that the behavior of Hall quantum effect in graphene is made due to relativistic nature of the charge carriers in this material .In a certain amount of dislocations wave functions of zero energy graphene charge carriers, similar to the basic state wave function of nonrelativistic carriers in ordinary Hall quantum systems will not be substituted.

According to the researchers, the existence of such unsubstituted states (that are called critical) can explain why flat parts of initial Hall before increasing in  $4e^2/h$  Multiples are appeared from $+/-2e^2/h$  instead of appearing from zero.

They also believe that the existence of predicted waves in graphene structure can be a satisfying reason for the appearance of these unsubstituted states.[47]

The half-integer quantum Hall Effect observed in graphene show in fig 7.

$4e^2/h$  multiples in $+/-2e^2/h$  means  $\sigma_{xy} = \frac{4e^2}{h} (N + \frac{1}{2})$  , that N is Landau balance index[51] that can be understood from the

settled massless fermions in graphene. Quantum energy of electrical structure of geraphene in a magnetic field B is explained by  $E_N=\pm v_f \sqrt{2e\hbar BN}$  that  $\pm$  is referred to electrons and holes [53-54]. The important note is that the energy in N=0 is zero.

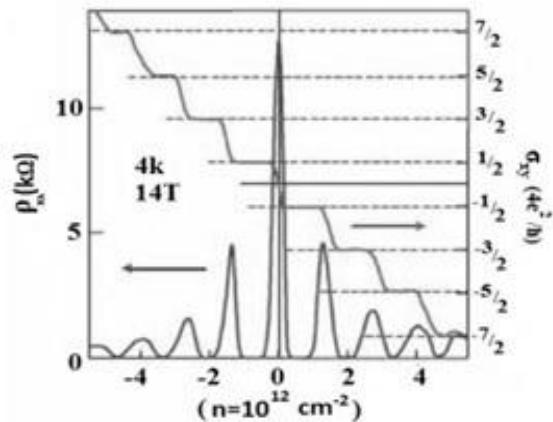


Figure 7. A diagram of Dirac's massless fermions in stable conditions (QED) with  $\sigma_{xy}$  in half integer form of  $4e^2/h$ .

Also graphene allows scientists to experiment some pseudo real effects that they are only theoretically experimentable .one of these effects is called Klein tunneling ,that was formulated by Swedish physicist Oscar Klein in 1929. Tunnel effect in quantum physics indicates that how come sometimes particles can cross through a barrier that usually blocks their way .for higher barriers, quantum particles have less chances to cross. Despite all of these, this is not true about the electrons that they move inside the graphene. In some cases they move like there are no barriers in front of them. High conductivity frequency for Dirac fermions for infrared ray among noticed spectrum range, is indicated by  $\pi e^2/2h$  constant.[54, 55]

$T=(1+1/2\pi\alpha)^{-1}$  and  $R=1/4\pi^2\alpha^2T$ , R reflectance and T optical transmittance for normal incidence light (that  $\alpha=2\pi e^2/hc\approx 1/137$ ) and electron charge e and c speed of light and h Plank's constant).and opacity is  $(1-T)\approx \pi\alpha\approx 2.3\%$ . The phrase R&T in fundamental constants expression explains one result of structure and electronic property of graphene[56].

The reflective index of single layer graphene is  $n=2.0 - 1.1 i$  [57] that is obtained from the visible region and has slight difference with reflective index of graphite. Generally graphite and graphene reflective indexes is  $n=3-(ic/3\lambda)$  (where  $c=5.446 \mu m^{-1}$  and  $\lambda$  is wave length) [58].

Due to the high electrical conductivity of graphene, it is predicted that graphene transistors (fig 8) should be very faster than silicon transistors .for better speed and performance in computer chips they should become smaller, that it's not possible for silicon .therefore graphene parts can be placed in smaller chips.

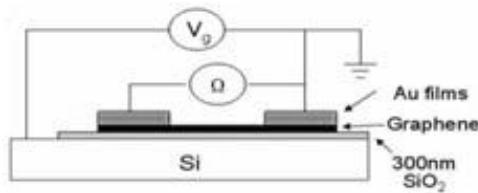


Figure 8. A scheme of gas sensor's graphene field effect transistor

Thus, graphene is completely clear and also can conduct electricity, it can be used in touchable screens, optical boards, and solar cells .also with combining only 1% of graphene to plastic, plastic becomes electrically conductive.

And also adding slight amount of graphene to plastic, increases plastic's thermal resistance to 30C and mechanically reinforces its strength.

This property can be used in order to make very strong, thin, elastic, lightweight materials .and even it is predicted that in the future satellites, airplanes, and cars can be made from new composite materials of graphene.

Also complete structure of graphene, makes it very suitable for production of very sensitive sensors, that can reveal smallest level of pollution. Even an absorbed molecule on the surface of graphene can be revealed .In a research both theoretically and experimentally it has been shown that single intersection point of charged particle energy bands in a phase space (called Dirac's point) is separated to intersection point of plasmaron quasi particles and also to a generated closed loop between charged bands and plasmaron. These results for instance show that graphene with these new characteristics can be used in Photonic industries in order to make Terahertz lasers.

In fact, by using plasmaron quasi particles, very small devices can be made, that simultaneously use electron and photon properties.

Mircea Dragoman says: << in graphene switches, electromagnetic field is turned on and off easily ,by applying a direct voltage , more over these switches have a good property, and that is when they are off, they repel electromagnetic field and when they are on ,they make very little dissipation in it [59].

Romanian and French scientists say that, it is possible to use graphene on order to make very fast microwave switches. These switches can be replaced with switches that are commonly used in communication applications like internet , cell phones .and also graphene can be used in rechargeable lithium ion batteries (RLBs), and in Electrochemical double layer capacitors (EDLCs) as clean energy devices.[60]

Graphene and chemically modified graphene (CMG) are very suitable options for various usages like energy storing materials, paper like materials, polymer composites, liquid crystal devices, and mechanical oscillators, as well as a variety of studies involving the use of CMG to make new materials. [61-63]

So far, four different methods are used in the production of graphene:

1. Chemical vapor deposition (CVD) and woven together growth
2. Layering micromechanic graphite, this method is called scotch tape or Layering, the resumption of last works in layering micromechanic graphite was patterned.
3. Woven together growth on the surface of electrical insulation
4. Making colloidal suspensions

Electromechanical layering leads to the production of little graphene. That can be used in fundamental studying. Although using the chemical deposition of vapor on the metal substrates will lead to big single or multilayer graphene .and allows the production of graphene based carbon materials by using CVD substrate less, improved plasma CVD by using radio frequency, Aerosol pyrolysis, synthesis of temperature, to be provided. But the growth of uniform single layer graphene is still a challenge in this field.

The method of producing graphene and CMG with graphite colloidal suspensions (such as graphite oxide)have properties such as scalability , versatility and compatibility with chemical operating methods, and also possibility for producing in great scales [61]. And so result study plasma waves and magnetoplasmons waves in surface purity Graphene and with impurity in high frequency [64-66], and you can see Magnetoplasmon excitations in Graphene in [67]

## V. SINGLE HETEROJUNCTION

Currently most of common structures are for studying the effect of size -quantum single heterojunctions .the junctions between semiconductors is different from Eg bandgap. In junction, there are steps in energy band that bound the motion of the carriers. These steps can be studied as walls of the potential well .the deviation of conductive tape  $\Delta E_c$  can be calculated by the difference in electrons affinity in materials.  $\Delta E_c = X_2 - X_1$  and valance band Can be written as  $\Delta E_v = E_{g1} - E_{g2} - \Delta E_c$  [68] also well's potential is size quantization ,that is made by the deviation of  $\Delta E_c$  in one side and junction's electrostatic field in other side. This is similar to inversion layer in MOSFET's structure, that only one type of carriers are Quantized.

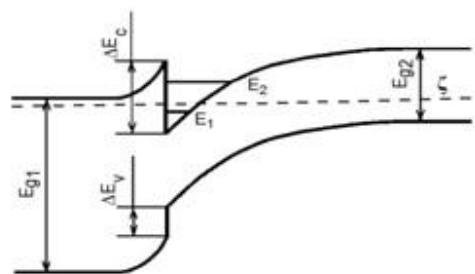


Figure 9. The diagram of a single hetero-junctions tape

Figure 9 shows a typical diagram of anisotropic heterojunctions between N and P type semiconductor .and it seems to be similar to MOSFET structure. In both, an inversion layer is considered as potential well and causes the generation of quantization energy near common part. Their main supremacy is in the quality of common part in hetero junctions compared to MOSFET single common part si-sio<sub>2</sub> by choosing a semiconductor with good sorting lattice, the density of surface states can be reduced to  $10^8 \text{ cm}^{-2}$  that is few times smaller than MOSFET structure. And such low density with automatic common part constantly cause fluency in carriers near to channel's common part. In the modulation-doped structure -x Al/GaAs<sub>x</sub> Ga<sub>1-x</sub> As , the found values for  $\mu$  increases to  $10^7 \text{ cm}^2/\text{s.v}$ ,while for best MOSFETs it is  $\mu = (5-4) 10^4 \text{ cm}^2/\text{s.v}$ .Therefore pressure broadening of quantum size balances is very little in multi structures.

Density of states ( $n_s$ ) in heterojunction channels is calculated by deviation band  $\Delta E_c$ .

Also semiconductor's doping balances make heterojunctions. For Al/GaAs<sub>x</sub> Ga<sub>1-x</sub> As systems, mostly density can't reach  $10^{12} \text{ cm}^2/\text{v.s.}$

## VI. HEMT (HIGH ELECTRON MOBILITY TRANSISTOR)

HEMTs are transistors with high electron mobility, and they are also called as HFET (Hetero structure FET) or MODFET (Modulation -Doped FET)[69] .

These transistors are field effect that are a combination of a junction between two materials and different bandgaps (in other words they have heterogeneous structure) that is usually a combination of GaAs & AlGaAs.

The invention of HEMT is usually attributed to Takashi Mimura. HEMTs are divided into 3 types Lattice matched HEMT (LHEMT), Pseudomorphic HEMT (PHEMT), Metamorphic HEMT (MHEMT).

In LHEMTs lattice constants of two settled materials in two sides of hetero junctions are the same.[70]while in PHEMT lattice constants of two materials are slightly different[71-73] (for example InGaAs/AlGaAs [74]),and in MHEMT, lattice constants are significantly different ,therefore it is usual ,in these types of HEMTS to grow a buffer layer between the two materials in order to reduce and compensate the differences .[75-77]

The main difference between MOSFET and HEMT is that in HEMTs some kind of channels are used instead of charge injection region used in MOSFETs (fig 10).

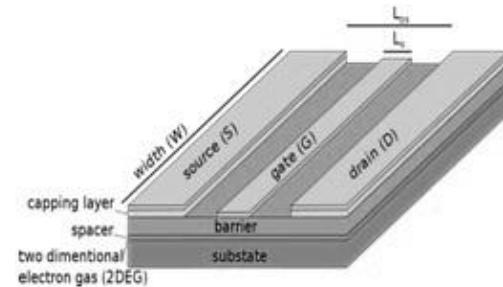


Figure 10. scheme of MOSFET structure

Field effect transistor's transconductance, seems to be proportional to the motion of carriers and the reason of choosing doped modulator structure in field effect transistors is their extreme motions.

In order to complete, a solution for controlling the carriers in doped modulator structure should be found. And at last, this problem can be solved by establishing schottky contact gate in doped materials with wide gap.

If the thickness of these layers is small enough, then the depletion layer overlaps in some common parts and schottky junction; and layer servers with wide gap is ionized ,and therefore this layer plays the role of dielectric, becomes similar to MOSFET multi structure. The density of 2D electrons linearly changes with respect to voltage. These field effect transistors usually are called HEMT for example fig 11. [78].

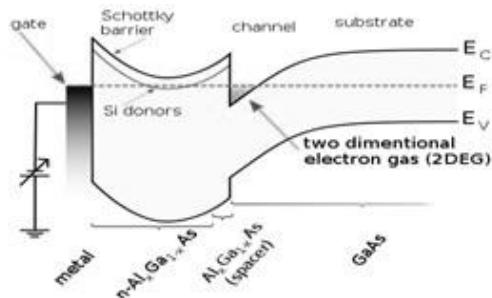


Figure 11. Band structure in GaAs /Al Ga As hetrojunction based HEMT

However, using structures with doped modulator field effect transistors can partly increase the mutual conductance. Two other parameters are switching characteristics time and energy in each single switch, that in comparison with standard transistors, the effect of built field is decreased by using GaAs pile.

HEMTs are used in conditions that high gain and low noise in high frequency are required .HEMTs have the ability to illustrate the current gain for frequencies bigger than 600GHZ and power gain for frequencies bigger than 1THZ. Currently some companies, design superfast computers by suing HEMTS. HEMTs also are used in DBS receivers[79] for electronic war systems such as radar and also for astronomical radio messages .[80]

## VII. QUANTUM HETEROSTRUCTURES

One year after the discovery of Hall's quantum effect in silicon MOSFET, the inversion layer in quantum heterostructures (Heterostructures structures) was seen for the first time.[81,82] To build such structure, first, it is necessary to choose a suitable pair of semiconductors ,in order to present a high quality heterostructures. One of the most important requirements is the constant equality of the two materials lattice. Because, lack of this condition, will cause a dislocation and mismatch with high density near common part, that will significantly decrease the quality of the junction, and also will block the visibility of quantum effects.

One of the reasons of measuring Hall quantum effect is standardization of the resistance. And it is shown in fig 12. This figure shows Hall quantum effect based on an electromagnetic field for a heterostructures building GaAs-Al<sub>x</sub>As In the temperature of T=1.2K.

In this curves, R<sub>H</sub> steps are very carefully chosen based on two fundamental physical constant, respectively Plank's constant, and electrical charge e.

And they are not based on their typical material, combination, construction, and coordination geometry, other external factors, and even uniformity of the magnetic field .this property is unique in all fields of solid state physics. Hall ordinary resistance as an example, like other resistances is based on the details of sample, coordination geometry, its construction, imperfections of crystal (such as impurities, and its asymmetry), and test temperature.

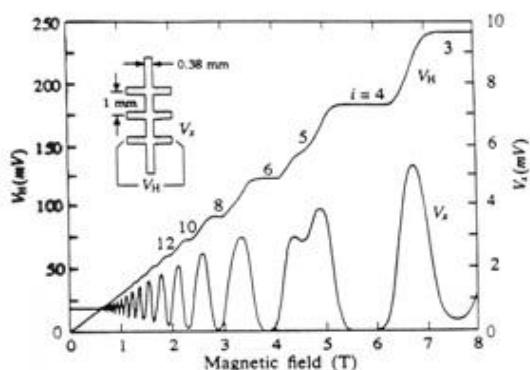


Figure 12. V<sub>H</sub> hall voltage and V<sub>X</sub> longitudinal voltage of quantum Hall effect based on electromagnetic field for a heterostructures building GaAs-Al<sub>x</sub>As in the temperature of t=1.2 K .electrical current is constant and equal to  $\mu$  25.5A and the electrons constant density n= $5.6 \times 10^{11}$ [83]

This heterostructure building is similar to MOSFET, but here a semiconductor with big energy gap (e.g Al<sub>0.3</sub> Ga<sub>0.7</sub> As) is established instead of the insulator. And therefore electron gas is established in very perfect and smooth section of the common part of two semiconductor crystals. Unlike the MOSFETs, the density of charge carriers in this system is generally constant and therefore, the magnetic field must be changed in order to reach quantum Hall condition.

Ionization emitters in Al<sub>x</sub> Ga<sub>1-x</sub> As Crystal (x is an integer between 0 and 1) works similar to gate voltage, and because of that 2D electron gas is established in such buildings even without applying external gate voltage. In fact, due to the differences exist between energy bands of these two heterostructure Semiconductors, silicon impurities in Al<sub>x</sub> Ga<sub>1-x</sub>As section approach to ionized junction section, and their electrons are transferred to GaAs section, near to the common part of semiconductors. This transmission of the charge causes the occurrence of powerful electric fields and a bend in the edge of conduction band near to the common part that will result to establishment of 2D electron gas.

For this electron piece, also electrons are confined in a narrow channel with an approximate width of 5 nano, and the shape of potential well is similar to silicon MOSFET state.

Although the production of these pieces is difficult, but due to the flat and perfect common part of two GaAs & Al<sub>x</sub> Ga<sub>1-x</sub>As in heterostructure buildings, a very slower background for the motion of the electrons in common part is provided.

The other difference between MOSFETs and them is their higher system temperature ( $\approx$ K4.2°), and in smaller magnetic fields (8 Tesla in comparison with 13 Tesla in MOSFETs) quantum Hall Effect is visible.

Also more mobility for electrons is achievable, and therefore the critical environmental condition is lower than MOSFETs in this experiment.[84]

GaAs-Al<sub>x</sub> Ga<sub>1-x</sub>As &InP-In<sub>x</sub> Ga<sub>1-x</sub> As can be mentioned as some of these heterostructure semiconductors.

As briefly mentioned in above ,the most common pair of semiconductors are used for establishment of quantum heterostructures GaAs-Al<sub>x</sub> Ga<sub>1-x</sub> As ,that have good lattice compatibility in each X alloy .and therefore they can be used in order to make heterojunction with different deviation band. Among the III-Vsemiconductors, there are some other ideal multi pairs such as InP-In<sub>0.55</sub> Ga<sub>0.45</sub> As.

However, in this pair and some other pairs for a constant combination, there is a lattice compromise, and therefore it does not allow  $\Delta E_c$  and  $\Delta E_v$  to change. Other groups of semiconductors are rarely used for the production of quantum heterostructures.

One of the technical requirements in establishment of terminated heterojunction.

Is the layering with variable combination that its thickness does not exceed from single layers.

Figure 13 shows the necessity of such sharp junction .It is obvious, that for establishing a smooth junction, the resulted potential well is wider and very shallower.

This will decrease the distance between the balances and will ban the visibility of quantum -size effect, and other requirement is the establishment of more complex and more visible impurity. Currently, the most common technology in the production of quantum heterostructure is [78] MBE.that is one of the most advanced methods in the growth of crystals.[85-88]

In this methods some atoms (or molecules) of required elements such as Ga,Al ,As and some impurities for doping from different sources under very high vacuum conditions are directed to the bottom layer, and they establish a layer from the required combination and provide the doping balance. The other suitable method is Chemical vapor deposition by using the combination of Metal-organic chemical vapor deposition (MOCVD) [78] that is not very expensive and complex, and has less possibility for controlling and performing. However it allows the growth of the heterojunctions with required sharpness and a structure with advanced profile including super lattices. Also study quantum heterostructures in[16].

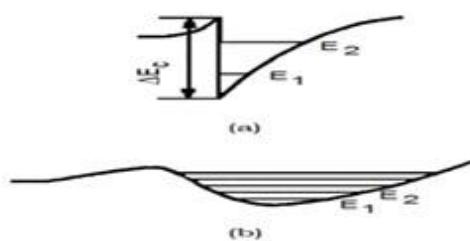


Figure 13. The potential profile of conduction band edge for sharp (a) and low gradient (b)

### VIII. QUANTUM WELLS AND SUPER LATTICES

Quantum well is a potential well with discrete energy values. And heterojunction diagram with an extra layer with thin gap can be called a quantum well. And the only difference between them and thin film is in the shallower potential well for electrons and holes .this event is the result for energy special values (En) that is calculated by the equation of shallow well[89].

In such well there are limited quantum balances equal to  $\lfloor \sqrt{2m\Delta E / \pi\hbar} \rfloor + 1$  that [...] means the integer part of a component , m and  $\Delta E$  respectively are effective mass and deviation in relative bands .

At the top of the quantum well, there are some high energy states with continuous energy spectrum, so that high energy carriers can't go from one layer to other layers, and their energy is not quantized.

Quantum well in semiconductor is shaped by having a material such as Gallium arsenide that is sandwiched between two layers with wide gap band of one material such as Aluminum arsenide.

Unlike single heterojunctions in heterostructures, similar to thin films, quantization size is available for both types of the carriers.

These are double heterostructures or quantum well.

Now we discuss a structure with double heterostructures similar to fig 14, and also its band diagram deformation. If the width of central thin gap layer ((a)) is been reduced.

We start from some values of (a) ,the neutral central part disappears in the layer(fig 14b)and whole the layer is filled by a charge that gives space with ionized  $eN_D$  density( $N_D$  is materials doped balance with narrow gap ).

It is easily shown from Poisson's equation, that in this case, the potential inside of the well will have parabolic shape with amplitude from equation (7).

$$\Delta\varphi = \pi e N_D a^2 / 2\epsilon \quad (7)$$

If  $a$  reduced more, the energy difference  $e\Delta\varphi$  will be reduced to a smaller value than  $kT$ . Therefore we can ignore band bending and assume there is a rectangular potential well with a width of  $a$  , and depth of  $\Delta E_c$  inside of the conduction band. (fig14c)

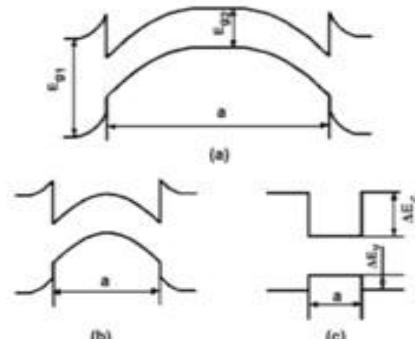


Figure 14. The diagram of a double heterostructures for various widths of the layer with narrow gap.

The set of material parameters for quantum well structures is of immense importance because of its usage in the development of theories, extraction of experimental data, and the proper design of devices[90].

Quantum well has many usages in diode lasers, that red lasers can be used for DVDs, and ace lasers, infrared lasers in optical fiber, or in blue lasers.

They are used in production of HEMTs in low noise electronics, and they also can be used in the production of infrared photo detectors. [91]

The main property of quantum well structures is high stability and less parameter swings, specially in the structures with optical sensitivity it has special importance in television systems with night vision.

Now, if multilayer structures with many swings of quantum well iteration , and similar to a single well is grown (fig 15)they can be divided in two to groups with respect to the layers thickness (b)with wide gap (gaps energy):

If  $b \geq A100^\circ$  then neighbor sells don't have any effect on each other, and they are called Multi Quantum Well(MQW) (for example InAlAs/InGaAs [92]),and are used as a sample in optical absorption laboratory that absorbing a single well for measurement in them is not sufficient, and if it is less , the

energy spectrum barrier of the system changes ,and the possibility of tunneling between wells , as it happens for atomic balances in crystals will result to quantum energy balances for the tapes ,which this property will result new structure ,called superlattice.

Superlattices can be officially assumed as a mediocrity between 2D and 3D systems.

Figure 15 shows a schematic view of superlattice with heterogeneous structure

That  $d$  is superlattices period, and it is consist of one semiconductor with a thickness of  $d_1$  and other semiconductor with a thickness of  $d_2$ , so that  $d=d_1+d_2$ .

The height of barriers in conduction band capacitance are respectively  $\Delta E_C$  and

$\Delta E_V$ . According to the figure we can see difference in the band between two semiconductors, increases the Band offsets  $\Delta E_C$  and  $\Delta E_V$  for conductance bands and capacitance.[93]

Super lattices and quantum wells have many usages in computer industry.[94]

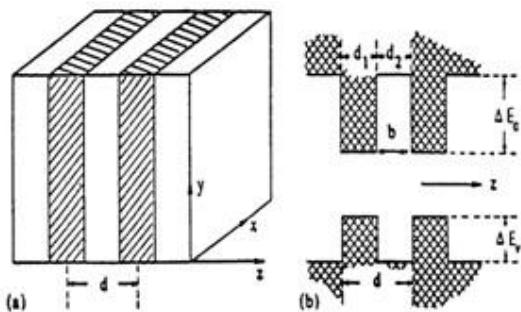


Figure 15. (a)super lattice with heterogeneous structure with swing  $d$ .(b)super lattice unit cell that is consist of two materials ,with the thickness of  $d_1$ and  $d_2$

## IX. DELTA AND NIPI-SUPER LATTICES LAYERS

Delta layers are an example of systems with bounded electrostatic pure charge, these layers are semiconductors with very heterogeneous doped profile, where all impure ions are focused in a very thin layer (ideally –single layer) [78 ,95]and the carriers made by the ionized impurity , remain near to their impurity layer by their charge .

The impurity's electric field  $F=2\pi eN_i/\epsilon$  ( $N_i$  impurity's surface density) is buffered by free electrons with the density similar to  $N_i$ . And the produced potential well has a shape that is typically shown in Fig 16.and it is given an approximate equation from equation (8):

$$V(z)=-\frac{me^4}{\epsilon^2\hbar^2}\left[\left(\frac{15\pi^3}{8\sqrt{2}}N_i^2\alpha_B^4\right)^{\frac{-1}{10}}+\sqrt{\frac{2\sqrt{2}}{15\pi}\frac{Z}{\alpha_B}}\right]^{-4} \quad (8)$$

That  $\alpha_B =\hbar^2/me^2$  is the effective Bohr radius.

In the potential well related to the top equation, there are many quantum balances and the total energy spectrum is expressed from equation (9):

$$E=E_N + [ (P_x + P_y)/2m] \quad (9)$$

That ( $P_x$  and  $P_y$  are related momentum components) is given for quantum –size systems and  $E_N$  is achieved from Schrödinger equation with a potential as top  $V(z)$ .estimation shows [96] that for a large enough  $N_i$  , the number of filled balances are equal to :  $[5.3(N_i\alpha_B^2)^{\frac{1}{5}}]$

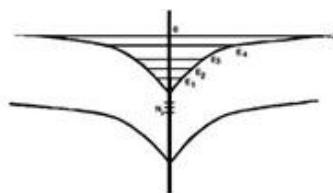


Figure 16. The band diagram of a single delta layer

One special sign of delta layers is the possibility to calculate the very high density of quantum –size carriers  $N_i \sim 10^{14} \text{ cm}^{-2}$  that is significantly bigger than other discussed structures.

In addition to delta single layers, in some issues, structures are consist of many grown layers. And they are studied .these are called nipi super lattice [95].

These are alternatively Consist of p and n types delta layers that their diagram is shown in figure 17.

If the density of carriers in n and p layers is equal, the whole system is not in equilibrium state including free carriers, and has saw tooth potential profile.

Sub band ignition, produces unstable electrons and holes that are separated in electric field .changes in band diagram by their charges, will change a set of important properties that are determined by their band structure, such as absorption spectrum.

Apart from ignition with voltage bias between n and p type layers, a similar effect can be achieved by using selected electrodes .in other words nipi super lattices can be studied as semiconductors with tuned bond diagram.

Their practical usage is in light sensitive elements and they can be used as photo detectors in the range of wavelengths that are bigger than homogeneous semiconductors.

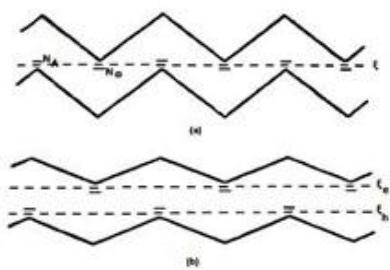


Figure 17. nipi super lattice (a) in balance (n) under ignition .Dash lines show the chemical potential balance in equilibrium state and also electron  $\xi_e$  and hole  $\xi_h$  balances.

## X. HELIUM SURFACE

It is well established that electrons on helium surface are an almost ideal two dimensional electron system.

They form the cleanest example of a two dimensional electron gas that, at sufficiently low densities and temperatures (where the potential dominates), will form a two dimensional electron crystal alled Wigner crystal [97]. In the bulk this system undergoes ca solid-liquid phase transition at a temperature  $T_m = 2e^2(n\pi)^{1/2} / (\epsilon_{He} + 1)k_B\Gamma_m$ , which is much higher than the Fermi temperature  $T_F = \pi nh^2/k_Bm$ . Here  $\epsilon_{He}$  is the dielectric constant of helium,  $m$  the electron mass and  $\Gamma_m$  is the plasma parameter at the melting temperature. Therefore, such electrons obey the classical Boltzmann statistics and their phase diagram can be calculated using classical approach.

Lindeman's melting criterion [98] tells us that the thermodynamic state of a classical coulomb system is determined by the quantity  $\Gamma = \langle U \rangle / \langle K \rangle$  which is a measure of the ratio of the mean coulomb potential energy to mean kinetic energy. Thus, for  $\Gamma \leq 1$  the kinetic energy predominates and the system behaves like an electron gas. At intermediate densities  $1 \leq \Gamma \leq 100$ , the electron motion becomes highly correlated or liquidlike. At high densities  $\Gamma \geq 100$  the coulomb potential energy predominates and the electrons are expected to undergo a phase-transition to form a periodic crystalline array.

Experimentally the liquid-to-solid transition in the bulk takes place for a value of the coupling constant [99]  $\Gamma_m = 137 \pm 15$  and computer simulations by Kalia et al [100]. indicate a firstorder melting  $\Gamma_m = 118-130$  in good agreement with experiment. Superficial electrons on helium films also form a very interesting system to study the many-body properties of 2D screened systems. In this case the screening is provided by the image charges in the substrate beneath the film. The screening effect can drastically change the electron-electron interacting potential, going from  $1/r$  to  $1/r^3$ , through varying external parameters such as film thickness and dielectric constant of the substrate. Peeters [101], using a phenomenological approach got a reduction in the phase diagram of this electron system in comparison to the bulk case. Saitoh [102] using an analytical approximation for the angular frequency of the transverse phonon combined with the Kosterlitz-Thouless melting criterion, got a melting transition in this system in agreement with Jiang et al. experiments [103].

C`andido et al.[104] using computer simulation, studied the thermodynamical, structural and dynamical properties of this two-dimensional electron system.

Experimentally, the melting temperature of the Wigner crystal on thin helium films adsorbed on dielectric substrates was measured by Jiang et al. [103] through the electron mobility and by Mistura et al.[105] using microwave cavity technique.

## XI. CONCLUSION

According to the top discussion it can be concluded that all these examples such as MOSTFETs, graphene and etc. include a phenomenon called 2DEG (2 dimensional electron gas) that is rooted from quantum Hall effect .2DEG structure is usually used for the enhancement of electron conductivity in semiconductor devices and thus superconductivity on 2 dimensions (you can see [106-108] ), making electron and optic devices smaller and more accurate, perfect layering .and also it has special usage in electronic, telecommunication, optic, photonic and electro optic industries. Particles absorb radiation and high frequency waves, increased conductivity [64-66] and superconductivity [109] and among the properties are evaluated at and negative magnetic survey research [110].

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