A Review Paper on Tunnelling Effects in Integrated Circuits and Quantum Computing

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***Abstract*: This paper gives an insight on the quantum effects in Integrated circuits. As the IC's are getting smaller and smaller, the quantum effects are becoming more and more pronounced; hence we are approaching a dead-end in this technology. In the end an alternative to this problem is briefly discussed i.e. Quantum Computing**

I. INTRODUCTION

As the fabrication technologies are becoming more advanced with time, the IC technology is becoming more and more space efficient or compact, particularly the VLSI technology which uses MOS transistor as its circuit's basic entity. As the size of MOSFET is decreasing consequently so is the gate length, now as this length gets smaller and smaller the Quantum effect become pronounced, and thus the laws of classical mechanics becomes erroneous, our model and understanding of MOSFET is largely based on the Classical laws of mechanics and electrostatics. When we use this Quantum phenomenon for processing of bits, the computing is called Quantum Computing. Hence, both the abstract working and need of Quantum computing have been discussed.

Quantum Mechanics is built around the uncertainty of state, strictly speaking of System‘s state. This discipline of Physics is a probabilistic model of the possible states of the system as opposed to the Classical Mechanics. Here a clarification is called for the statement just given, the probabilistic model is not due to entropy of the system or our incompetence of measurement of data but the inherit property of the nature, given our current mathematical modelling of systems. The effect which we will encounter again and again as the size of the transistor becomes smaller and smaller is Quantum tunnelling.

Quantum tunnelling is phenomenon when system surmounts an energy barrier it cannot surmount according to classical laws, to be in a new state. This is quite fascinating, if you follow physics closely, but if you are and electronics student your life just got harder. As we were discussing in first paragraph, as gate length decreases the probability that a charge carrier in source will surmount the potential barrier and tunnel to drain drastically increases, hence resulting in noise. Due to this transistor looses much of its functionality. This is when we enter the realm of Quantum computers.

We are now more equipped to discuss what actually Quantum Computing is, formally it is the branch of data operations which uses the Quantum theory to perform data operations on the digital data, this is the new branch of digital electronics, one would have to say at this point that to realise such a computer one needs to be an expert at Quantum Mechanics, data operations and electronics.

To be more precise, I will say that to begin with, first we develop intuition about Quantum Mechanics, then we consider its consequences in IC's, then we develop models which deal with the shortcomings by using completely new operations based on these phenomenon.

In this report I won't be doing the in depth analysis of Quantum computers but rather try to discuss the physics which is at play here, I will be discussing these effects more qualitatively than quantitatively.

II. QUANTUM MECHANICS AT HAND

In 1921 Erwin Schrödinger gave wave function associated with the wave nature of a particle. This wave equation is derived from the state of the particle or system, state being the energy of the particle or system.

Schrödinger's Equation

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t) + V(\mathbf{r},t)\psi(\mathbf{r},t)$$

i is the imaginary number, $\sqrt{-1}$.
$\hbar$ is Planck's constant divided by 2π: 1.05459×10^{-34} joule-second.
$\psi(\mathbf{r},t)$ is the wave function, defined over space and time.
m is the mass of the particle.
∇^2 is the Laplacian operator, $\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$.
$V(\mathbf{r},t)$ is the potential energy influencing the particle.

(Image)

Now, having this tool at our disposal we now look for interpretation of this Equation. Bell argued that the square of the normalized Schrodinger‘s equation is probability of the particle being present at the coordinate for which the function was evaluated.

When dealing with this equation for a particular function with boundary conditions, i.e. there are regions of different energy, one realises that the wave function extends into the region into which classically a particle should not exist. To make life easier we only consider time independent wave equation, meaning that the wave function is independent of time.

Boundary conditions: These are coordinates in space at which the potential energy influencing the system changes. The equation now must be solved for the different regions, i.e. using different potential in wave function, with keeping in mind that at boundary the adjacent wave has the same amplitude. For sake of simplicity, we do not solve the equations rigorously.

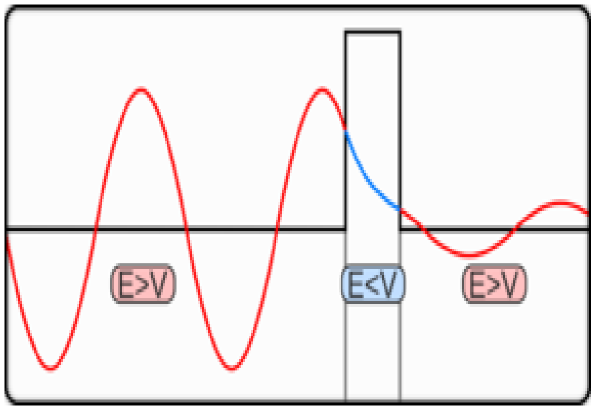
Now, before we proceed further to quantum tunnelling, I would like discuss more about quantum mechanics. It is assumed that the reader knows why there is need of quantum mechanics, but if you are new to quantum mechanics I bet you are having a hard time dealing with the plausibility of this theory. I don't claim to solve this riddle but rather give you a counter intuitive notion which will either make coherent with quantum mechanics or disbelieve every physics theory that you thought you knew. I will take example of Newton's laws of motion. At that first instance you understood the Newton's law of motion based on equation F=ma, (where F is force, m is mass and a is acceleration) you didn't raise any eyebrows, as it came intuitively to you that it is a practically reasonable equation, because you see it all around you, For ex pushing gate open, throwing a ball, catching a ball etc. it all comes to mind when you are testing the plausibility of Newton's Laws of motion. This is the mistake you make with understanding the quantum mechanics, you do not have any practical examples to relate to the principle, and in fact it violates the nature as you sense it. But that is the whole point that your perception of the nature by your own senses is deceiving you, because it is not always the same as you see or hear it. To capture nature a more elegant way is to describe it using mathematical functions which go way beyond our perception of things.

III. QUANTUM TUNNELLING

It was somewhat necessary to have that argument before we proceed to Quantum Tunnelling according to me and I do know that it may be a subjective argument but it was worth the risk of sharing it with you. If you have come to terms with wave equation, you must follow this pretty easily in mathematical terms, but if you find it plausible or practical you are ready to envisage into the dark worlds of Quantum mechanics.

When the Boundary conditions are such that the potential influencing the particle or system is greater than the energy of the particle or system, then particle or system according to classical physics cannot exist in such region, but the wave functions does extends into this region.

Now this is the scenario (described next) which is of great importance to us, consider three regions , two having potential energy lower than that of the particle's energy and one in between these two having a potential greater than the energy of the particle. Now if we write the boundary conditions and find out the wave functions for these three regions we note that the functions observed are, in region 1 and 3, is a periodic sinusoidal function, but in region two it is an exponentially decreasing function dependent on space coordinates.



We now take important points from this discussion, and they are

1. The wave function value at the boundary between the region 1 and 2 is same & between 2 and 3 is the same.
2. Now if region two is much wider than the wave at region 3 has small amplitude as compared with that of region 1. However if the length of region two gets smaller and smaller the amplitude of the wave in region 3 increases, now recall the Bell's principle , and realise that now the probability of the particle being present in the 3 region is ever so increased.

These two points must be saved for later use.

Wave function in region 2: It is an interesting question to ask whether the function depends upon any parameters in the region, but first as you may have guessed that the exponential nature of the wave at question of the fact tha potential of region is greater than the energy of the system. So it is somewhat safe to say it depends upon difference of the two energies. When you actually solve the functions you find that the exponential function's power depends directly on the difference of the two energies, so higher is the potential associated with the region, sharper is the wave function going to decrease in this region.

The above was just a qualitative discussion of the Quantum Tunnelling effect, but it does consider most if not all the factors associated with the Quantum Tunnelling effect.

With this we conclude our discussion of Quantum Tunnelling.

IV. DIGITAL ELECTRONICS

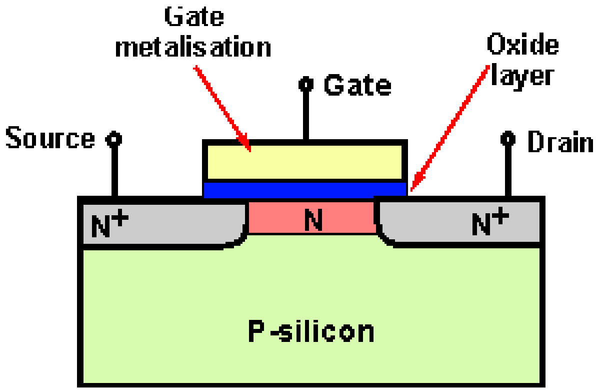
In this era of Information technology, one must wonder how all the data is actually stored and manipulated by computers. The answer to this is that the data is stored as digital data i.e. in 1's and 0's. And these 1's and 0's are interpreted as voltage high and low respectively in electronics and therefore IC's. If we were to use any other technology, these 1's and 0's will find another interpretation than voltages, they just describe two distinct states.

V. INTEGRATED CIRCUITS AND QUANTUM TUNNELLING

To begin our discussion first it is necessary to address Integrated circuits. A major breakthrough achieved in IC Technology was the advent of VLSI technology. VLSI is based on computer simulations and then realisation of the digital circuits using transistors. The transistors which are being used are the MOSFETs which is short for Metal Oxide Semiconductor Field Effect Transistor.
Why MOSFET is preferred to other transistors

1. It has very high input resistance.
2. Fabrication is much simpler relatively.
3. CMOS is really power efficient.

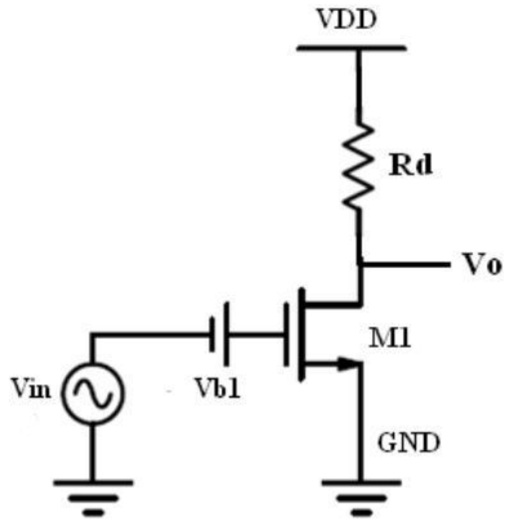
As we advanced into the age of information technology, it was the demand of time that the processors become more and more efficient and powerful. A simple solution was to still make the size of MOSFET smaller and smaller given that we want to keep the size of IC as small as possible.
Now let us consider the Structure of MOSFET and its working. It is expected that the reader is familiar with basic electrostatics, circuit theory and Semiconductor physics.
Consider the diagram shown below; to begin with as we see that a barrier potential is created between the source and substrate & Drain and Substrate, this region is going to act as our region 2 in the Quantum Tunnelling discussion.
When a positive voltage is applied to the gate terminal, due the electric field generated in the substrate region, due to this negative charge is going to accumulate at the substrate gate junction. If this field is above threshold value than the charge accumulated will also consist of free charge carriers too. This creates a channel between the source and the drain region, and now if the potential difference is created between the source and drain (biasing), a current flows through the circuit.



Basically, transistors operates in three modes

1. Cut-off mode: Gate to source voltage in below threshold and hence no channel is created and no current flows in transistor.
2. Active mode: In this region Gate to Source Voltage is above threshold and the current is exponentially dependent on both the drain to source and the gate to source voltages.
3. Saturation mode: In this region, the gate to source voltage is above threshold but the drain to source voltage is above gate to source voltage, so the channel is discontinued at the drain end and the current becomes independent of drain to source voltage.

In IC technology the given below circuit is incorporated, so that a huge network of the MOS is established, which is an interdependent network.



Now we realise that to make IC more space efficient we have to decrease the size of the MOSFET. The channel length is a good indication of the size of MOSFET. In 2014 Intel created IC's with 14nm channel length while it is expected to drop below 10nm by 2017.
But it is not without consequence that we can decrease the length of channel in MOSFET, which brings us to Quantum Tunnelling.

VI. TWO TIER 3 REGION MODEL OF MOSFET

This section requires that the reader has basic knowledge of Statistical Mechanics and Semiconductor physics.
Before I describe this model, it should be understood that these many levels of depths at which this discussion can be taken into, but I shall only describe which is under my comprehension.
The easiest model is to assume first the source substrate region where region 1 and 3 is source and substrate respectively and region 2 is depletion region, this constitute the tier one now consider tier two which is similar except that the region one is substrate and region 3 is drain and region 2 is their depletion region.
Now work a little and create this model in your mind or better sketch it out. You must have one question by now, that is if substrate is a region 1 or 3 than the channel length shouldn't matter for tunnelling effect's significance.
Now the Statistical Mechanics knowledge will come in handy, we consider two points

1. The majority of the charge carriers are present in the valence band whose wave function is limited to the parent atom or few of its adjacent neighbours.
2. The current is due to the charge in Conduction band, the concentration of the charge carriers can be increased in this band by external bias or high temperature.

If we say that the external bias is not as high, the majority charge is in valence band and with tunnelling effect, the electrons which jumped from source to substrate will have their wave functions limited to few neighbours, and hence the probability of these charges being present in drain is next to null if channel length is large, however if channel length becomes smaller there will be a current due to tunnelling effect.

Now consider if the external bias is high, then the current due to bias is already high that the tunnelling current in conduction band becomes insignificant but if the channel length decreases the tunnelling current in valence band becomes significant and hence a noise is observed.

Now as I said earlier, the depth of this topic cannot be quenched by a mere qualitative approach and that too with one which only scratches the surface.

This Analysis can be made more pronounced if we consider the effect of the Statistical distribution, and then using Fermi-Dirac statistics to actually determine the charge distribution and then compute the wave functions and hence quantum tunnelling due to this distribution and take a meaningful average, to estimate tunnelling effect as whole, tunnelling will then greatly depend on temperature.

So we now realise that we are exhausting the resource of channel length very quickly and soon enough we will have no option in this direction for optimising the IC technology. This looks like the dead end for the IC technology.

With this I conclude the topic of Quantum Physics in Integrated Circuits. Now we shall look at the Alternative for this dead end briefly.

VII. QUANTUM COMPUTING

This is the last topic of this paper; we are not going into any details about Quantum computing but take a brief look at this exciting new technique to handle data and its manipulations.

Quantum computing as stated before uses Quantum Mechanical phenomenon to describe and manipulate data. We are not going to study Quantum computers and its structure, but one must realise that it is certainly not same as where we left off IC's, it is something fundamentally new.

In quantum computing, the data is represented by Qubits instead of definite bits. These Qubits could be any reasonable Quantum mechanical property of the system, such electron spin, discrete momentum or position. For electron spin, these Qubits together describe different states, when Qubits superimpose or entangle with each others. Because of the probabilistic nature of the Quantum quantities, these Qubits can hold different states in sample space, now we can model these Qubits to be favourably in on sate or the other by initial conditions. One interesting fact is that where a classical computer uses 2^n bits there quantum computer uses only n bits to describe the same number of states. But the problem with quantum computing is that the whole operations is based on the probabilistic nature of the Qubits and their superposition or entanglement so very advanced and complex algorithms must be used for data operations. Now due the efficiency of Qubits to describe information it is also a faster than classical computers.

On conclusion, there is vast domain to be exploited in quantum computing both at modelling of data and Quantum Mechanics knowledge and this is bound to be the future of computer, as of now Quantum computer are only believed to be in its infancy.

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