PERFORMANCE ANALYSIS OF CNTFET AND MOSFET FOCUSING CHANNEL LENGTH, CARRIER MOBILITY AND BALLISTIC CONDUCTION IN HIGH SPEED SWITCHING

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ABSTRACT

Enhancement of switching in nanoelectronics, Carbon Nano Tube (CNT) could be utilized in nanoscaled Metal Oxide Semiconductor Field Effect Transistor (MOSFET). In this review, we present an in depth discussion of performances Carbon Nanotube Field Effect Transistor (CNTFET) and its significance in nanoelectronic circuitry in comparison with Metal Oxide Semiconductor Field Effect Transistor (MOSFET). At first, we have discussed the structural unit of Carbon Nanotube and characteristic electrical behaviors between CNTFET and MOSFET. Short channel effect and effects of scattering and electric field on mobility of CNTFET and MOSFET have also been discussed. Besides, the nature of ballistic transport and profound impact of gate capacitance along with dielectric constant on transconductance have also have been overviewed. Electron ballistic transport would be the key in short channel regime for high speed switching devices. Finally, a comparative study on the characteristics of contact resistance over switching capacity between CNTFET and MOSFET has been addressed.

KEYWORDS

CNTFET, MOSFET, schottky barrier, channel length, carrier mobility, MFP, SCE, DIBL, transconductance, gate capacitance, ballistic conduction, contact resistance.

1. INTRODUCTION

Semiconductor based technology has gone through a tremendous advancement in recent decades. In the field of manufacturing integrated circuit, Moore's law dominates the evolution in the number as well as the size of transistors. But in nanoscale fabrication, field effect transistors have been suffered from direct source-drain tunneling because of short channel effects [1]. As MOS infrastructure continues to scale down deeper into the nanoscale, various non-ideal characteristics, substantially different from MOSFET are aroused. Carbon Nanotube (CNT), the rolled structure of graphene, renders itself to multi-disciplinary applications in nanoelectronic circuits and removes those effects [2]. The field effect transistors consisting of CNT are called

CNTFET and recently they have attracted the attention as possible building blocks of future nanoelectronics due to their distinctive structural, electrical and mechanical properties [3]. These provide notable characteristics over MOSFET using the semiconducting properties of CNT like high carrier mobility, large MFP (mean free path) [4], ballistic conduction [5], suitable contact resistance [6], fast switching speed and less heat dissipation [6, 7]. Carbon nanotube based transistors can work as a molecular electronic device in terahertz region in comparison with silicon based transistors.

Although CNT has less reliability and greater cost problem, it can play a vital role in nanoelectronic devices such as transistors, memory components [8, 9] etc. because of its excellent electrical conductivity and high dielectric properties [10, 11]. Therefore, Field Effect Transistors have been tried to be constructed from CNT to surmount the limitations of Si-MOSFET such as carrier mobility, channel length [8], ballistic conduction, transconductance [9, 10], heat dissipation, threshold voltage etc. [10-12].

2. CARBON NANOTUBE (CNT) & CARBON NANOTUBE FIELD EFFECT TRANSISTOR (CNTFET)

CNT is a carbon allotropic variety which comes from the fullerenes family. It is made of nano sized carbon atom and rolled in seamless cylindrical form of single atomic layered thick grapheme sheet [13]. Fig. 1 (a) shows a CNT which is made from one sheet of graphene rolled in cylindrical structure which is called Single Wall Carbon Nanotube (SWCNT) and Fig. 1 (b) shows Multi Walled Carbon Nanotube (MWCNT) where multi-layers of graphene are rolled as a concentric tube [14-16].

CNT based nano devices are comprised of wide range of nano structures. CNTFET could be used as valve or controlled switch in electronics. Carbon Nano Tube Field Effect Transistors for NEMS are emerging day by day not only in IC industry but also in medical science, mechanical system, automobile industry and recreational instruments [17].

(a)

(b)

Figure 1 (a). SWCNT and (b) MWCNT [14, 15].

CNT has two natures, metallic and semiconducting. The semiconducting natures of CNT is used to manufacture CNTFET device. For the property of high conductivity, SWCNT is being largely used in CNTFET fabrication [16].

3. CNTFET PERFORMANCES OVER MOSFET PERFORMANCES

CNTFET has distinct nanoscale properties that has been absent in MOSFET microelectronics. Thus MOS technology is not promising alternative for fabricating dynamic nano devices. CNT could be used in nanoscaled MOSFET in gate region over dielectric substrate. So, that gate oxide has little effect in CNTFET than MOSFET. Fig. 2 (a) shows the schematic view of CNTFET and Fig. 2 (b) the same view of MOSFET. Circuit performance in CNTFET and MOSFET, we need drain current against drain voltage curve (I-V) for various gate voltage which is shown in Fig. 3. There are linear curve region in MOSFET curve which is not available in CNTFET, which has gradual saturation region providing better electrical behavior than MOSFET.

Figure 2. (a) Carbon Nanotube Field Effect Transistor (CNTFET) [18] and (b). Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) [19]

Figure 3 (a) & (b). I-V characteristics (Drain current vs. Drain voltage) for different gate voltage of CNTFET and MOSFET respectively [20, 21].

3.1 High carrier mobility over long channel length

At CNTFETs, having long channel length, the mobility of carriers is high. Fig. 4 (a) shows that SiO₂ provides the better path for the electronic transport between the electronic channel and

dielectric layer as compared to other high- dielectrics. When channel length of CNTFET is modified with chemical etching, this effect is seen which increases the mobility of carriers. But in case of MOSFET, due to some scattering mechanisms, such as phonon scattering, surface roughness scattering, columbic scattering from interface, bulk charge impurity scattering etc., the mobility of electrons become affected. Although, Fig. 4 (b) shows, it also provides electric transport for SiO₂ dielectric layer which is nearly identical to CNTFET [22-25].

Figure 4 (a). Variation of mobility for different channel lengths (micrometer) of CNTFET and (b). Variation in mobility with different dielectric material in MOSFET [25].

Figure 5. Measured effective carrier mobility (μ_{eff}) vs. effective electric field (E_{eff}) in MOSFET for different substrate body biases at 85 K. ($W= 100 \mu\text{m}$, $L= 28 \mu\text{m}$) [26].

Again, as channel length is increased, carrier mobility is increased. Due to short channel effect (SCE) for short channel devices, carrier mobility becomes lower. But in case of CNTFET, the problem of SCE is not effective and there are no difficulties due to scattering. So, carrier mobility is independent of channel length. Moreover, bulk and interface charge impurity scattering dominates at low effective electric field and that is why carrier mobility is decreased. At high effective electric field (E_{eff}), surface roughness and photon scattering becomes effective and again effective carrier mobility (μ_{eff}) is degraded. In these cases, channel length of the MOSFET is kept constant. Figure 5 shows measured effective carrier mobility with various substrate body biases (V_{bs}) at 85 K. At low temperature, mobility is separated for different V_{bs} and low E_{eff} as

Columbic scatterings dominate at these regions. Larger V_{bs} leads to mobility, μ_{eff} decreasing for same low E_{eff} due to reducing of electron density in the channel. As the scattering mechanisms are not dominant in CNTFET devices, so scattering hardly affects the carrier mobility [24, 26].

3.2 Effect of short channel length and effective channel length

Channel length of CNTFET is small compared to the MOSFET. At the shorter channel length, ballistic transport of carrier occurs in CNTFET and shows better performance. For CNTFET, as the channel length of device decreases, the performance of the device upgrades due to ballistic conduction. But in case of MOSFET device, as channel length decreases, short channel effect (SCE) becomes more dominant. A MOSFET device will have the problem of SCE when the order of the magnitude of the channel length is same as the depletion layer widths of the source and drain junction [1, 2]. Fig 6 (a) & (b) shows the channel length scaling for different gate and drain voltage for MOSFET and CNTFET respectively [25, 28].

When an MOS device is in saturation, the effective channel length actually is decreased such that $L_{eff} = L - L_{short}$. Effective channel length depends upon different properties of materials such as capacitance, dielectric constant etc. Fig. 6 (a) shows that as drain voltage increases, the effective channel length decreases, for different types of dielectric materials. In case of CNTFET, the material properties may not reduce the effective channel length [2].

Again, for MOS devices, when channel length is reduced, the threshold voltage decreases. This is caused due to the decrease in potential barrier, which introduces Drain Induced Barrier Lowering (DIBL) [1]. For CNTFET, as there is no problem of short channel effect (SCE) like MOSFET, no shift of threshold voltage causes here. In case of MOS devices, due to SCE, as channel length decreases, there is a significant increase in leakage current and DIBL, which reduces the switching speed of device [2]. But in CNTFET, leakage current and DIBL is independent of effective channel length. Besides SCE problem, if the channel length is increased, parasitic resistance will be increased and MFP (mean free path) for scattering will also be increased. That is why drain current will be decreased with certain gate voltage (Fig. 6 (b)). But, channel length of CNTFET is smaller than MOSFET and that's why, problems due to parasitic resistance are more effective in MOSFET than CNTFET [27].

Figure 6 (a). Effective channel lengths vs V_{ds} for various dielectric materials in MOSFET [25]. And (b). Channel length scaling according to characteristics graph of I_D vs. V_G of CNTFET. The channel length, $L_{ch} = 15, 10, 5$ nm and gate ZrO_2 thickness nm $t_{ox} = 2, 2, 1$ nm (for dash-dot line, solid line and dashed line respectively) [28].

There is an optimization needed for fabricating CNTFET considering channel length as long channel length provides high carrier mobility where short channel length dominates in ballistic conduction which is not present in MOSFET.

3.3 Transconductance variability due to gate capacitance and bias voltage

If the transconductance of a CNTFET is g_m , then it can be defined by this following equation [29]:

$$g_m = \frac{\mu \left(\frac{C_{gg}}{L} \right)}{\left(\frac{V_{ds}}{L} \right)} \quad (1)$$

Where, C_{gg} is the gate capacitance, μ is the carrier mobility and L is the gate length. Here it can easily be found that the greater the carrier mobility and gate capacitance and lower the gate length, the higher the transconductance. For a CNTFET, μ and L are fixed and gate capacitance is defined by the equation [29]:

$$C_{gg} = \frac{2\pi K \epsilon_0}{\ln\left(\frac{4t}{d}\right)} \quad (2)$$

Where, t is the dielectric thickness and d is the diameter of CNT. For top/bottom gate CNT, t is high because of its highly dielectric nature. High- t value increases gate capacitance C_{gg} , which enlarge the transconductance g_m value. On the other hand, for a SBCNTFET, lowering or elimination of the schottky barrier at the nano-tube metal surface by the high electric field at the dielectric metal surface, transconductance will be affected [29]. Effective gate capacitance will be found dividing gate capacitance by $2d$ (d = CNT diameter). It is measured $\sim 5.5 \mu\text{Fcm}^{-2}$ for CNTFET, which is better as compared to about $\sim 2.4 \mu\text{Fcm}^{-2}$ for MOSFET [30].

Figure 7 (a). the channel conductance and (b). transconductance vs. gate voltage in CNTFET when $C_{ins} = 0.4 \text{ pF/cm}$ (dashed line in right axis) and $C_{ins} = 90 \text{ pF/cm}$ (solid line in left axis) [31].

Fig. 7 (a) & (b) shows the behaviors of channel conductance and transconductance as a function of gate voltage, V_G for low and high insulator capacitance, C_{ins} . In the quantum capacitance limit (high C_{ins}), the channel conductance is quantized in units of $4e^2/h$. It is experimentally found that Fermi level is observed at the bottom of first sub-band with larger gate voltage showing quantization effect. That's why V_G dominates in CNT potential [31].

Figure 8 (a). Typical variation of Capacitances with V_{DS} in MOSFET. (b) Typical variation of Capacitance with V_{GS} in MOSFET [30, 32]

Moreover, the MOSFET capacitances are non-linear and a function of the dc bias voltage. Fig. 8 (a) shows how capacitances correspond with increased V_{DS} voltage. The decrease in capacitances with V_{DS} is caused by the decrease in depletion capacitance as the voltage increases and the depletion region widens. Fig. 8 (b) shows that when the V_{GS} voltage increases past the threshold voltage (for low V_{DS} values), the MOSFET gate capacitance also increases because of the formation of an inversion layer of electrons in the MOS channel and an accumulation layer of electrons under the trench bottom. This is why the slope of the gate charge curve is increased once the voltage goes beyond the Qgd phase [30, 32].

3.4 Effect of contact resistance on switching capacity and drain current

The contact resistance depends strongly on the atomic structure in the contact region when intermolecular nanotube junctions are formed. An interesting feature of this junction is the intuitive dependence of conductance on the contact length, l . Fig. 9 (a) and Fig. 9 (b) shows the conductance values for armchair-armchair and zigzag-zigzag tube junctions respectively. It is also interesting to note that when the tubes are in-registry, the conductance values are high and comparable to ideal tubes. Therefore, this simple end-end contact geometry is an excellent way of connecting multiple tubes in device applications [5].

On the other side, when the nanotubes are displaced shortly from in-registry configurations, then the conductivity of the inner tubes gets reduced huge significantly. Thus, rapid switching between high and low conductance states could be achieved and fast atomic scale switches can be structured by using these end-end junctions. It is also found that the contact resistance can vary several orders of magnitude with atomic scale movement. This modulation of contact resistance improves the switching speed of CNTFET. In MOSFET, altering channel resistance affects switching capacity [5].

Figure 9 (a). Variation of conductance at the Fermi energy as a function of contact length, l for the (10, 10)-(10, 10) junction (Armchair CNT) where unit cell length $a_z = 2.46$ Å. (b). Variation of conductance with l for the (18, 0)-(18, 0) junction (Zigzag CNT) where $a_z = 4.26$ Å [5].

Figure 10. Relationship between Ion and specific contact resistance ρ_c in 45nm NMOS device (contact area = $0.045 \mu m \times 1 \mu m$) [33]

Again, MOSFET channel resistance is reduced with scaled channel length, but on the other hand, the accordingly scaled contact area causes an increment in contact resistance if specific contact resistance is not scaled. Fig. 10 shows that technology to reduce specific contact resistance has a major impact on drain current as well as transconductance in deep sub-micron MOSFET [33].

3.5 Ballistic conduction and increased charge density

CNT shows ballistic conduction at room temperature. For SWCNT, it is 200 nm scale. For MWCNT, both diffusive and ballistic properties are found. MOSFET does not show ballistic conduction because gate voltage of MOSFET holds some charge in the channel at the beginning [14, 31].

Figure 11. The charge density vs. gate voltage curve for CNT [34]

Fig. 12. Fraction of ballistic electrons (%) as a function of CNT length ($E = 1$ kV/cm) [20].

As ballistic conduction is non-resistive and scattering mechanism can be ignored, then current density is higher in CNTFET than MOSFET. Fig. 11 shows the variation of charge density (Q_{CNT}) at the beginning of the channel with increasing gate voltage (V_G). Gate voltage induces charges at the channel. As the gate voltage increased, the source-drain barrier lowers and then current flows between source and drain due to the flow of charge. If gate voltage is increased, more carriers flow through the channel due to ballistic conduction and so charge density in channel is increased which increases drain current. But in case of MOSFET, ballistic conduction is not possible and that is why ON current does not increase significantly with increasing gate voltage because charge density does not rise like CNTFET with varying gate voltage due to absence of ballistic conduction [3, 34].

Number of ballistic electrons are dependent on CNT length with low field step of 1 kV/cm shown in Fig. 12. For this low field regime, the main scattering event corresponds to electron-photon acoustic scattering. For larger tubes, 50% electrons are ballistic (ballistic curve is decreased slowly) and for smaller tubes, the electron ballisticity is reduced at first 200-300 nm, then going down almost in constant manner [20].

4. CONCLUSION

In recent future, fabrication of a single IC where transistors extending in three dimensions is called 3D VLSI technology, which could be the future of IC fabrication emerging the size: from tiny to tinier. But, it is restricted by the physical limits to transistor scaling due to source-to-drain leakage, limited gate metals and limited options for channel material. CNTFET could be an appropriate device for its small size and exclusive ballistic, heat dissipation and low resistive properties. In this study, various existing types of CNTFET and its distinct properties over MOSFET have been reviewed. Due to high dielectric material, mobility of carrier increases whereas channel dimension decreases rigorously. The special property of channel dimension leads to ballistic conduction due to large density in channel, presenting CNTFET as more suitable in nanoelectronic devices than MOSFET [35]. In addition, semiconductor memory devices can be fabricated by using CNTFET for its high on/off current will open a new era in nano-computing. This has to be mentioned that manufacturing by CNTFET is quite costly and CNTFET has lower reliability due to growth of misaligned CNTs in growth process and increasing leakage power and noise margin in metallic CNT. Also, manufacturing variation in doping, densities of tubes, static noise could increase the delay in functioning power [36]. Considering all of these, CNTFET becomes one of the most promising candidates for Si MOS technology and its stunning performance opens a door of new possibilities in the field of nanotechnology.

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