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A review on Carbon Nanotube Field Effect Transistors

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Abstract

Modern computers use silicon transistors as small as 14nm. These transistors have reached their limits. Carbon nanotubes are the speculated successor because of their advantages of electrical conductance, heat dissipation and stability. These characteristics should help reduce current limitations of silicon transistors. Implementation of carbon nanotubes is limited by manufacturing defects and impurities which, even small defects, significantly impact the efficiency of the transistor. Even differences in the interfacial thermal resistance could make current designs and materials obsolete.

Key words: CNT, FET, quantum tunneling, MOSFET, CNTFET

Introduction

A. Modern Silicon Transistors

Current transistors are primarily made from silicon. Silicon transistors come in multiple styles, one style being the Field Effect Transistor, or FET. The FET uses an electric field to direct the flow of electrons from a source, through a channel, which passes the gate, and into the drain as shown in Fig. 1. While the FinFET design has only been made as small as 14 nm, it proves to have great returns in performance.

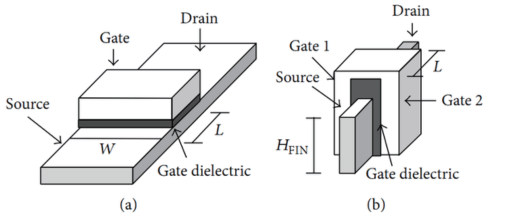


Figure-1 Comparison of MOSFET (a) vs FINFET (b). As seen in the image, the FINFET has multiple gates, allowing for more switches, and improving performance. [13].

B. Carbon Nanotubes

Carbon nanotubes are rolled up sheets of graphene. It may be single wall nanotube (SWNT) or multi wall nanotube (MWNT). Semiconducting SWNTs are of special interest because they are promising in producing semiconducting devices that rival devices made by traditional Si technology [8]. Since CNTs can act as either metals for high conductance or semiconductors to act as transistors, can have varying properties that may complicate the development of carbon nanotube field effect transistors. Despite metals having higher conductance, the effects of electron hopping is more prevalent which can limit the efficiency of the transistors. The semiconductor variant, however, is not so vulnerable and may be a better option [3]. Under current technology production of carbon nanotubes is not perfect and can develop differently in some areas. Chemical impurities make a large difference because of the electrical properties having a large impact on the actual operation of the device as a whole [4].

Discussion

A. CNTFETs as a solution to issues in silicon FETs

Use of silicon in the past as the primary material for MOSFETs has been effective as a material for a long time. However, problems like quantum tunneling, heat dissipation, and conductance have limited the size of silicon transistors. The goal of CNTFETs is to produce a transistor that is not only of similar or smaller size than traditional silicon FETs, but also one of higher performance and electrical efficiency [4]. Silicon FETs have reached limitations where electrical conductance and heat generation have become issues, and the design of the transistor to combat these has become increasingly important [5]. Due to CNTs' abilities as highly efficient semiconductors on a much smaller scale than traditional silicon semiconductors in today's transistors, CNTFETs are the possible solution to the issues arising from silicon transistors.

B.Decreased size of CNTFET

The number one goal in the long term of revolutionizing transistors is reducing their size. As size decreases, more and more transistors can get packed onto a plate. Recently the size of transistors has been slowing down, seen in Intel's 14 nm FINFET microarchitecture having been in use since Q3 2014 [10]. While microarchitectures such as this have been improved over the years with higher density chips and more efficient circuits, there are roadblocks that inhibit future designs that can reliably perform on a large production scale in sub 10 nm architecture [1].

CNTFETs aim to break these roadblocks with improved properties over silicon. With one of the dimensions of

CNTFETs being as small as 2 nm, it allows for incredibly fast switching of current [4]. For a long time, and even still, CNTs have been highly difficult to produce as purely semiconductors, and CNTFETs have lagged behind in performance from silicon transistors for years. In 2014, researchers at UW Madison created a method to isolate pure semiconducting carbon nanotubes with less than 0.01 percent metallic defects. By using pure carbon nanotubes, researchers were able to create 1 in by 1 in chips that when benchmarked against silicon, provided currents 1.9 times greater than its silicon rival, all while at the same dimensions of the silicon chip. While CNTFETs have been made down to the sub 10 nm size, there is still a long way to go before they are ready for mass production. [2].

C. Reduced temperature effect on CNTFET

MOSFET characteristics change dramatically when temperature changes. Due to transistors giving off large quantities of heat, this becomes a large issue if the heat is not dissipated. Silicon transistors will fail at 150°C, and before that, will have a dramatic loss in performance under high levels of heat [8]. The carbon-carbon bonds in the sp2 hybridization allow CNTs to be chemically inert, and carry current under high heat with little degradation, as shown in table 1.

Table 1: The effect of Temperature in CNTFET devices on the threshold voltage. The CNTFET can withstand temperatures much higher than that of a normal silicon MOSFET. This performance under high amounts of heat make CNTFETs more reliable than current silicon transistors [8]

THRESHOLD VOLTAGE W.R.T. TEMPERATURE

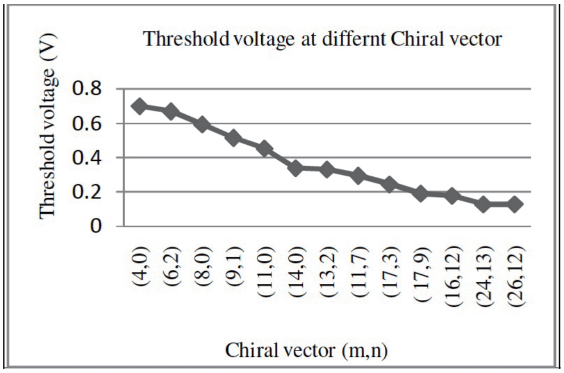
Effect of temperature on CNTFET devices	
Temperature (°C)	Threshold voltage (V)
27	0.210
47	0.210
67	0.210
87	0.210
107	0.202
127	0.198
147	0.194
167	0.191
187	0.187
207	0.180
227	0.164

D. Controlled threshold voltage of CNTFET through CNT modification

CNT's conductivity can be altered depending on the arrangement of atoms in the tube. This is referred as the chirality of CNT, and the chirality vector can be represented by integer pair (n,m).

In this case the circumference of CNT an be represented by chiral vector C=nx+my. The indexes of the vectors determine the conductivity. The CNT is metallic if x-y=3 or n=m [8]. It is important for CNT to perform as semiconductor, so the CNT will respond to the gate voltage. With different chiral vector pairs, the threshold voltage changes. Through the modification of CNT, we can control the threshold voltage of CNTFET.

Figure 2: Different chiral vectors corresponding to different [8]



E.The limitation and improvements of CNTFETs

The creation of carbon nanotubes is already difficult enough to make them reliably and consistently. Adjusting the charge of specific areas is even more difficult, but is very necessary for field effect transistors. The p-type portion of the CNTFET can already be created through methods such as contact optimization, but the n-type components is much more complicated. Size itself is a large obstacle in getting reliable results partially due to design and partially due to the need for specific ratios. New designs of CNTFETs are able to surpass modern designs using silicon, but reliability is only one of the issues [11]. From estimations fromusing known properties, carbon nanotubes should be able to become five times more efficient than transistors made of silicon [4]. Research into the properties of carbon nanotubes are not always positive. Research on the interfacial resistivity of CNTs has shown limitations in the materials that can be used with CNTs based on the ability to transfer energy between different materials [9].Sometimes, the unavoidable stray capacitance and large resistance leading to small electricity can also cause the problem for the further use of CNT transistors.

The future developments of CNT transistors

Changing material quality and device structure could have potentially beneficial results. In one design, IBM engineers set channel length to 10 nm , gate pitch to about 20-30 nm and CNT pitch to between 5 to 10 nm with the density of CNT 100–200 μm^{-1} (shown in Figure-6a).They tested this structure,comparing with silicon CMOS, to get great advantages (shown in Figure-6b). Another design, from Chinese engineers, involves a structure similar to FinFET, with each transistor containing 3 fins with high density over 125 μm^{-1} (shown in Figure-6c). This design gets much better velocity of transition of electricity and utilization of energy than silicon (shown in Figure-6d).These two examples indicate the way to improve the CNT from the internal structure to the design of the device to manage the CNT more efficiently to overcome the some defects in the application. [12]

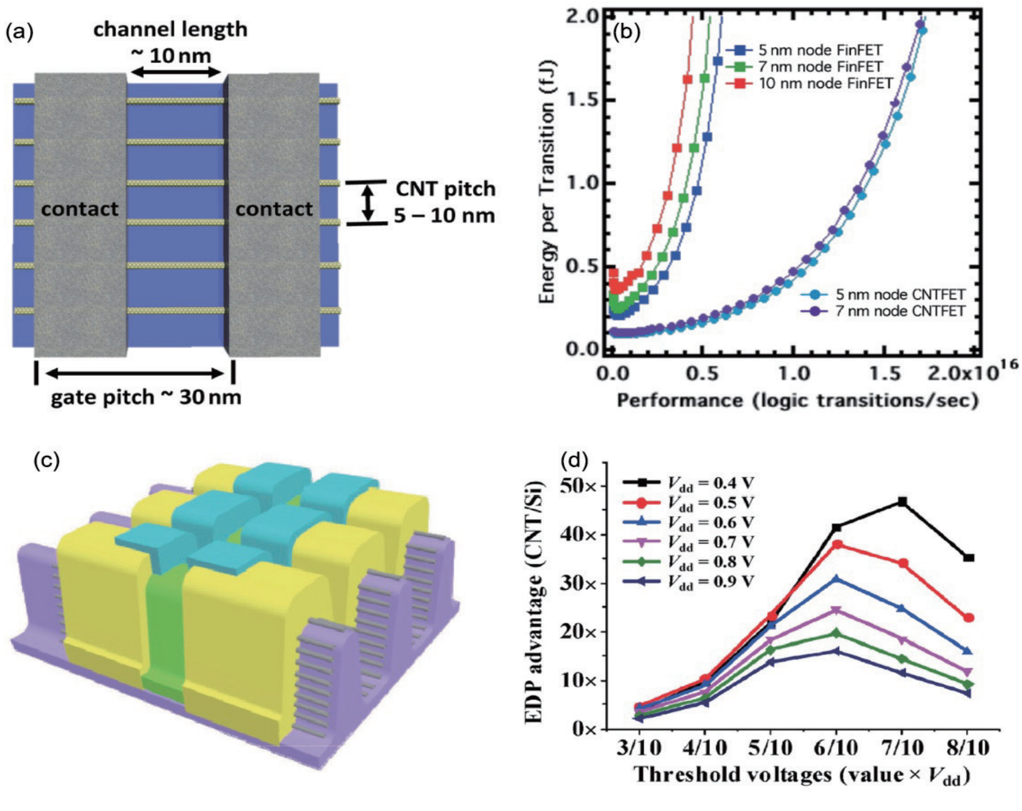


Figure-3: The effect of new designs of CNTFETs on the performance and threshold values [12]

Conclusions/Recommendations:

Advances in technology never come without problems. The use of silicon in transistors is nearing its end as physical limits are being reached. Carbon nanotubes are expected to be the next material to surpass its defects and push the limits of transistor to a new level to suit in the growing need for more efficient functions and smaller size in production. It has already been discovered that CNTs have superior properties for electrical conductance, heat dissipation, and is less susceptible to quantum tunneling. Despite these benefits, problems still occur, such as interfacial thermal resistance, production defects, and impurities. More consistent production methods and new designs need to be created before CNTFETs become a marketable replacement for silicon transistors. In the future, the new design and production of CNT transistors will make the wide use of such devices possible.

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