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Optimization of Source/Drain Doping Concentration of Carbon Nanotube FETs to Suppress Off-state Leakage Current while Keeping Ideal On-state Current

Berrin Pinar Algul[1] and Ken Uchida[1]
Dept. of Physical Electronics[1], Tokyo Institute of Technology, 2-12-1-S9-12, Ookayama, Meguro-ku, Tokyo 152-8552, Japan
Phone/Facsimile: +81-5734-3854, E-mail: berrin@neo.pe.titech.ac.jp

Abstract

The device parameters of carbon nanotube field effect transistors (CNFETs) with doped source/drain junctions have been studied in order to realize lower off-state leakage current (I_{OFF}) while keeping better on-state current (I_{ON}). It is demonstrated that, when the power supply voltage (V_{dd}) is greater than the bandgap (E_g) of CNTs, optimized doping concentration showing the lowest I_{OFF} exists. On the other hand, when V_{dd} is smaller than E_g, I_{OFF} monotonically decreases as doping concentration decreases, although the aggressively lowered doping concentration results in lower I_{ON}.

1. Introduction

Carbon nanotube FETs (CNFETs) have attracted growing interests because of their immunity to short-channel effects and excellent driving capability. Therefore, the characteristics of CNFETs have been investigated with respect to various device parameters. As a result, it has been demonstrated that the performance of CNFETs can be improved by optimizing the carbon nanotube (CNT) diameter (d_{CNT}) and the gate oxide thickness (t_{ox}). However, the impact of doping concentration (N_d) on CNFET characteristics has been less studied in spite of its importance on FET operations. Here, we provide the first comprehensive study on CNFET performance as a function of the doping concentrations. It is revealed that the optimization of doping concentration is a key to realize the best I_{ON}-I_{OFF} performance.

2. Device Structure & Simulation Method

Device structure used in our simulation is shown in **Fig. 1**. The characteristics of CNFETs are simulated under full ballistic transport assumption by utilizing Landuer's formula [1, 2]. The portion of CNTs, uncovered with the electrodes, is assumed to be chemically doped. Because of the 1-D nature (small density-of-states) of CNTs, the Fermi energy level in the doped region increases rapidly with an increase in the doping concentration. The doping concentration in this work is described by the Fermi energy level (E_d) measured for the conduction band edge (E_c). When the drain voltage is applied, the source and drain Fermi levels are separated into $E_{F,S}$ and $E_{F,D}$, respectively.

3. Results and Discussion

We first examined the dependence of drain current (I_d) versus gate voltage (V_g) characteristics on source/drain doping level (E_d). **Fig. 2** shows I_d-V_g characteristics of (25,0) CNFET for E_d ranging from 0.1eV to 0.9eV. As E_d decreases from 0.9eV to 0.5eV, the lowest Id ($I_{d,\min}$) decreases in line with E_d. However, as E_d decreases from 0.3eV to 0.1eV, the leakage current increases unexpectedly. Moreover as for the I_{ON} (I_d at V_g of around 1 V), I_d saturates at E_d of 0.1eV, while no saturation is observed at E_d of 0.3- 0.9eV.

Physical mechanisms were studied to understand the increase of I_{off} and saturated I_d characteristics. **Fig. 3** shows $I_{d,min}$ versus E_d characteristics for 1-nm, 1.5-nm and 2-nm diameter of CNTs at V_{dd} of 0.8V. These points tend to decrease as E_d decreases. However, for CNTs with E_g of less than V_{dd}, the optimized E_d's, shown with arrows in the Fig.3, provide the lowest $I_{d,\min}$. Energy band diagrams were drawn to analyze the origin of E_d optimization. **Fig. 4** shows the energy band diagram of (25,0) CNFET with E_d of 0.5eV; $E_d > V_{dd} - E_g$ (a) and 0.1eV; $E_d < V_{dd} - E_g$ (b) at V_g of 0V with E_g of less than V_{dd}. It should be noted that energies between $E_{F,S}$ and $E_{F,D}$ except for those in bandgap contribute to I_d. In Fig. 4(a), only electron tunneling is observed. Whereas, in Fig. 4(b), hole injection from the channel to the source valance band is allowed, resulting in the rise of leakage current. Therefore, E_d lower than $V_{dd} – E_g$ increases I_{OFF}.

We then examined I_{ON} as a function of E_d as shown in **Fig 5**. Except for the lowest E_d, I_d is not affected by the change of E_d. Band diagram of CNTs with saturated I_d (E_d=0.1eV) and without saturated I_d (E_d=0.9eV) are illustrated at V_g of 1 V in **Fig. 6**. In the case of CNFET with E_d of 0.1eV, the bottle neck point is located inside the source region. As a result, carrier injection velocity is limited by E_d. While in CNFET with E_d of 0.9 eV the bottle neck point is within the channel, injection velocity is thus modulated by V_g. **Fig. 7** explains the effect of drain voltage on I_d at V_g of 1 V and $I_{d,min.}$. Considering the correlation between V_{dd} and E_g determining the tunneling energy levels, drain voltage must be choosen to give lowest I_{off} and highest I_d level.

Fig. 8 summarizes the conditions to obtain low level of I_{off}, while having a relatively high level of I_d.I_{off} decreases with source/drain doping level and CNT diameter is decreased. However, I_d is also in the tendency of is being slightly decreased. It is also seen that doping level control is dominant over small d_{CNT} considering $I_{off,min}$ as it was already explained in Fig. 6.

4. Conclusions

We performed a detailed simulation for CNFETs with doped source/drain junctions. It is demonstrated that CNTFETs with doped source/drain junctions can show lower I_{off}, while maintaining better I_d with the help of correct parameters.When energy bandgap, $E_{g,}$ is greater than the power supply voltage, I_{off} can be supressed by decreasing E_d. On the other hand, when E_g is smaller than V_{dd}, the opimization of E_d is required to achieve the lowest $I_{d,min}$.The control of the doping level of source/drain junctions significantly reduces the leakage current and increase the I_{ON}/I_{OFF} ratio.

References

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[2] K. Uchida *et al.*, *Appl. Phys. Lett.*, **91** (2007) 203520.

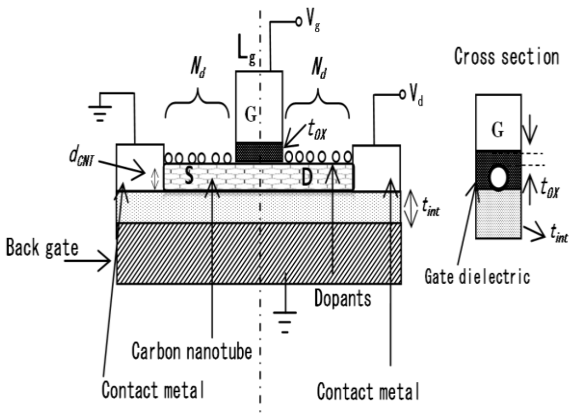

Fig. 1. Schematic of CNFET structure simulated in this work. The cross-sectional view of the structure along and across the channel direction.

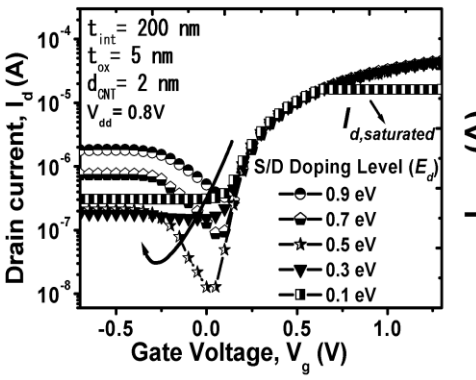

Fig. 2: I_d-V_g characteristics of (25,0) CNFETs with E_d from 0.1eV to 0.9eV. As E_d decreases from 0.9eV to 0.5eV, I_{off}, which is defined as the I_d at V_g=-0.5V, decreases in line with E_d. For E_d level decreased from 0.3eV to 0.1eV, I_{off} increases.

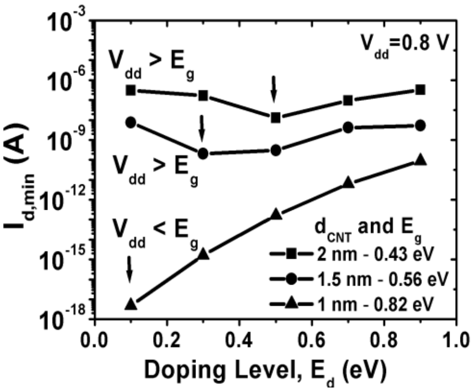

Fig. 3: $I_{d,min}$-E_d change for different CNT diameters. $I_{d,min.}$ points shift to lower I_d values for smaller diameter of CNT.

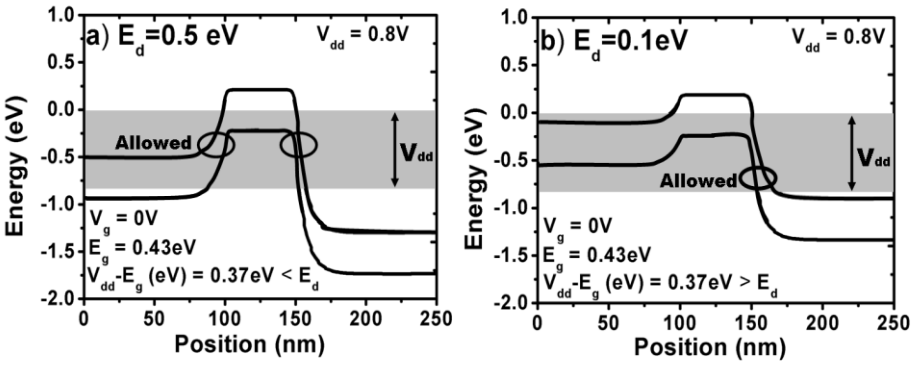

Fig. 4 Energy-band diagram of (25,0) CNFET for E_d of **(a)** 0.5eV and **(b)** 0.1eV. When E_g, is bigger than supply voltage, V_{dd}, I_{off} can be supressed well. If E_d is smaller than V_{dd}-E_g (V_{dd}>E_g) hole injection from channel to source valance band is allowed around $E_{F,D}$ resulting in the rise of leakage current.

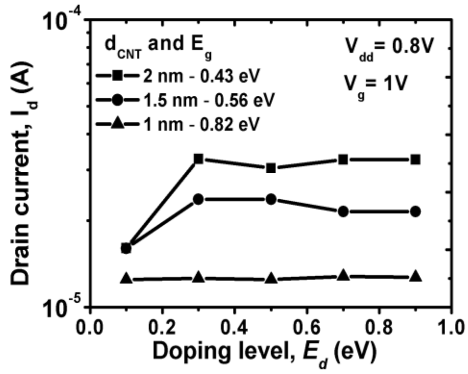

Fig. 5: I_d-E_d characteristics for different CNT diameters. Except for the lowest E_d value, I_d show near constant level of current.

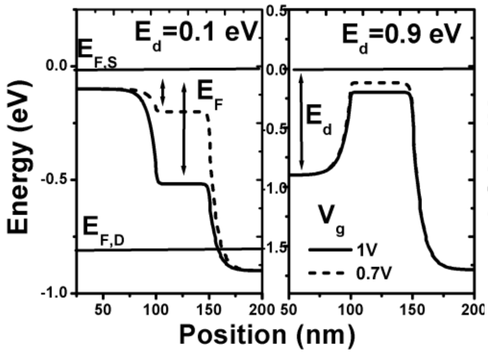

Fig. 6 E_c profiles at the gate voltage of 1V of with saturated I_d (E_d=0.1eV) and unsaturated I_d (E_d=0.9eV) CNFET with E_d=0.1eV as carrier injection is limited by E_d.

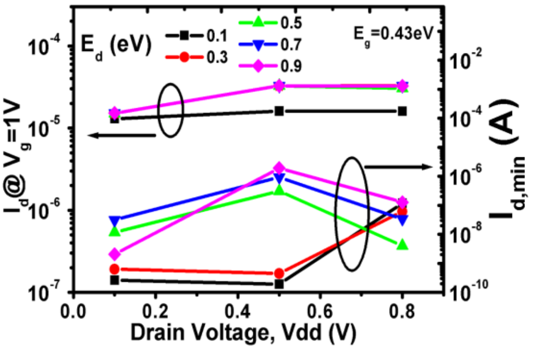

Fig. 7 Drain voltage dependence of I_d@V_g=1V and $I_{d,min.}$ of (25,0) CNFETs for E_d from 0.1eV to 0.9eV. When E_d is equal to 0.1eV and 0.3eV $I_{d,min}$ abruptly increases for V_d is bigger than E_g.

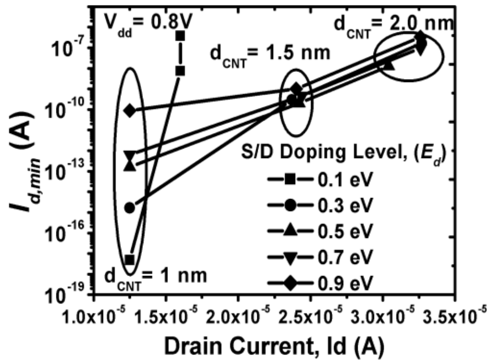

Fig. 8 I_d- $I_{d,min}$ for different E_d and d_{CNT}. Doping level control is dominant over small d_{CNT} considering $I_{d,min}$. I_{off} decreases as source/drain doping level and CNT diameter decreased.