Enhanced Performance of Carbon Nanotube Field-Effect Transistors Due to Gate-Modulated Electrical Contact Resistance

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Abstract

Due to their unique electrical properties, carbon nanotubes (CNTs) have attracted a great deal of interest for their potential in next-generation nanoelectronics [1,2]. While individual CNTs can exhibit favorable electronic properties, it is often the CNT/metal contacts that govern the behavior and performance of CNT devices [3,4]. Thus, it is important to develop a fundamental understanding of contacts to CNTs in order to fully realize the potential of CNT devices. Recent experimental work [5,6] has provided new insight by demonstrating that the nanotube/palladium (Pd) contact resistance depends on the contact length, and that appropriate control of the contacts allows for the realization of high-performance short-channel CNT field-effect transistors (FETs) with subthreshold swings that surpass those expected from conventional scaling theory. This last result is particularly important not only for technology, but also because it suggests that new paradigms govern the properties of these nanoscale transistors. For example, it has been suggested that modulation of the contacts by the gate, a phenomenon not usually observed in conventional transistors, could lead to such behavior [6].

In this work [7], we use numerical simulations to study these recent experimental measurements and explicitly demonstrate that the superior scaling behavior is due to a strong modulation of the contacts by the gate. This results not only in modulation of the band alignment at the contact, but also leads to a novel phenomenon where the subthreshold swing is dominated by gate control of the near-contact region in the channel. This gives rise to subthreshold swings for short-channel devices that are below what is predicted by standard theory, allowing for improved performance.

The simulated CNT FET is shown in Figure 1. For this work, we consider a (16,0) nanotube with a diameter (d_{CNT}) of 1.2 nm, which matches the average size of the CNTs in Ref. 5. We also consider two different contact geometries. In Figure 1a, there is metal both above and below the nanotube, as a model for a CNT completely embedded in metal. In Figure 1b, we consider a contact where the metal only sits on top of the CNT. To determine the transport properties of the FET, we use a self-consistent non-equilibrium Green's function (NEGF) approach [8] that allows us to calculate the low-bias current through the device.

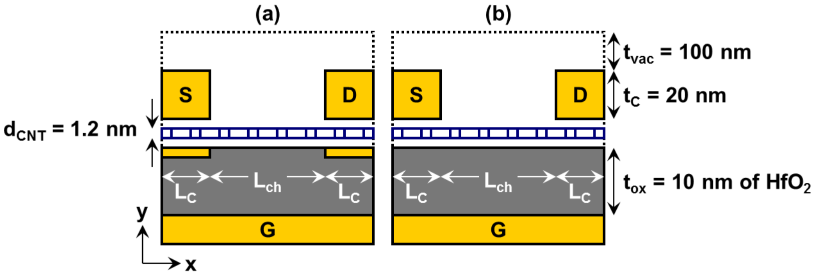

Figure 1. Schematic of a carbon nanotube field-effect transistor. In part (a) the source and drain metals are above and below the nanotube (embedded contact), while in part (b) the metal only sits on top of the nanotube (top contact).

Using the NEGF approach, we calculated the transfer characteristics of the CNT FETs for channel and contact lengths that match the experimental devices. The results are shown in Figure 2, where the experimental data is given by the symbols and the theoretical data is given by the solid lines. The top row of Figure 2 shows the results for L_{ch} = 40 nm, the middle row is for L_{ch} = 20 nm, and the bottom row is for L_{ch} = 15 nm. The left column shows the simulation results for embedded contacts (see Figure 1a), while the right column is for top contacts (see Figure 1b). The experimental data is the same for both columns. An important feature of the experimental data is the extremely good scaling of the transistor characteristics as the channel length is reduced. Indeed, comparing the experimental data for the channel lengths of 40, 20, and 15 nm in Figure 2, one can see that the subthreshold swing is essentially unchanged as the channel length is scaled down. While the thin HfO_2 dielectric provides good control over the FET channel, our simulations indicate that this by itself is not sufficient to explain the good subthreshold behavior. This can be seen by comparing the left and right columns of Figure 2. The left column shows the simulation results for the embedded contacts. In this case, the theoretical subthreshold swing is much larger than the experimental value for small channel lengths, and we see a poor fit to the experimental results. However, when we remove the metal below the CNT, the subthreshold swing is significantly reduced for the short-channel devices and we obtain excellent agreement with the experimental data, as shown in the right column of Figure 2. Thus, the geometry of the contact plays a crucial role in determining device performance and scaling, and the improved behavior upon removing the bottom metal indicates a strong influence of the gate on the contact properties.

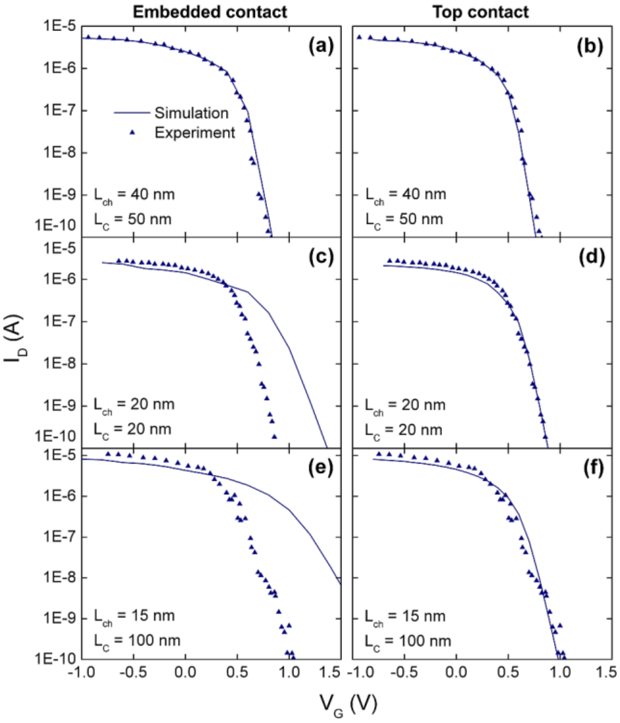

Figure 2. Current vs. gate voltage for short-channel CNT FETs. The top, middle, and bottom rows are for L_{ch} = 40, 20, and 15 nm, respectively. The left (right) column is the case for embedded (top) contacts. The symbols represent experimental results from Ref. 5, and the solid lines represent the results from numerical simulations.

In summary, we presented simulations of short-channel ballistic CNT FETs that explain recent experimental results using Pd contacts. We have reached the important conclusion that the contacts are strongly modulated by the gate when no bottom metal contact is present, allowing for lower subthreshold swings for short channels and improved scaling behavior. This result introduces important design considerations for CNT electronic devices, and should also apply to devices made of other nanomaterials such as nanowires and graphene.

References

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