On Gate Capacitance of Nanotube Networks

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Abstract—This letter presents a systematic investigation of the gate capacitance C_G of thin-film transistors (TFTs) based on randomly distributed single-walled carbon nanotubes (SWCNTs) in the channel. In order to reduce false counting of SWCNTs that do not contribute to current conduction, C_G is directly measured on the TFTs using a well-established method for MOSFETs. Frequency dispersion of C_G is observed, and it is found to depend on the percolation behavior in SWCNT networks. This dependence can be accounted for using an RC transmission line model. These results are of important implications for the determination of carrier mobility in nanoparticle-based TFTs.

Index Terms—Frequency dependence, gate capacitance, nanotube networks, percolation, transmission line model.

I. INTRODUCTION

THIN-FILM field-effect transistors (TFTs) featuring single-walled carbon nanotube (SWCNT) networks as the semiconductor channel have gained enormous attention for large-area, inexpensive, and flexible electronic applications [1]–[3]. For TFTs, a reliable definition of the gate-to-channel capacitance C_G is essential since it determines many key parameters such as drive current and carrier mobility. A reliable determination of C_G requires proper understanding of the SWCNT network properties particularly SWCNT density

and percolation behavior. A parallel-plate capacitor model, where C_G is calculated using its simple relation to channel area and gate dielectric thickness, is often used as a simplification [1]. This simple treatment can lead to an erroneous C_G , in particular, for TFTs with low-density SWCNT networks [2], [4]. Capacitance measurement can be performed by depositing a metal layer on the SWCNT network forming a metal–insulator–semiconductor (MIS) capacitor structure [3]. Unfortunately, this method will likely lead to an overestimation of C_G because it also includes SWCNTs that are present as isolated sticks having no contribution to current conduction in the channel [5], [6]. Apparently, a more reliable determination of C_G needs to reduce such false SWCNT counts and focus on SWCNTs that actively participate in percolation. In this letter, we will employ the well-established C_G measurement procedure for MOSFETs [7]. Specifically, capacitance measurement is directly performed on a TFT by grounding its source and drain terminals while sweeping the gate bias. By doing so, the isolated SWCNTs not electrically connected to the source (S) and drain (D) contact electrodes are effectively excluded. This approach has already been shown to be feasible for transistors with individual semiconducting SWCNTs [8]. In this letter, the C_G for TFTs with different SWCNT coverage will be determined in order also to unveil under what circumstances a simple MIS structure may suffice. Strong frequency dispersion of C_G is observed and can be well accounted for by using an RC transmission line (TL) model [9].

II. DEVICE FABRICATION AND CHARACTERIZATIONS

Heavily doped Si wafers were used for device fabrication. After the growth of a 150-nm-thick SiO_2 as the gate dielectric, the desired gate stack with a back-gate configuration was formed. The S and D electrodes consisted of a 40-nm-thick bilayer of Pd/Ti. Random SWCNT networks were formed by means of drop casting of SWCNT suspension onto the channel areas of length $L = 200 \mu\text{m}$ and width $W = 100 \mu\text{m}$; see Fig. 1(a). The SWCNT suspension consisted of pristine HiPco SWCNTs (1.1 nm in average diameter) dispersed in aqueous solution with 1-wt% sodium dodecylbenzene sulfonate. For each sample with a specific SWCNT suspension, the distribution, as also shown in Fig. 1(a), and, hence, the average density ρ (μm^{-2}) of SWCNTs were characterized by atomic force microscopy (AFM) at three randomly chosen locations. The average length l_{NT} of the SWCNTs was $\sim 1.5 \mu\text{m}$. An SWCNT surface coverage $p = \rho l_{\text{NT}}^2$ is defined to accommodate different nanotube lengths [6]. For the network in Fig. 1(a), $p = 6.5 \pm 2.0$ is obtained, and it is slightly above the percolation threshold $p_c = 4.236^2/\pi \approx 5.7$ [5], [6]. Current–voltage (I – V) measurements were performed on a Keithley 4200-SCS semiconductor analyzer. Capacitance–voltage (C – V) measurements were conducted by superimposing a small ac signal (30 mV in amplitude) at different frequencies, f_m , to V_{GS} . The bias

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Fig. 1. (a) Schematic diagram of a back-gate TFT featuring randomly distributed SWCNTs consisting of (blue broken lines) isolated tubes, (red dotted lines) tubes nonpercolated but connected to the S/D electrodes or the percolation pathways, and (black solid lines) percolated tubes, together with an AFM image in height mode of an SWCNT network with surface coverage $p = 6.5 \pm 2.0$. (b) Monte Carlo simulation results showing the variation of N_{TOT} , N_{PER} , N_{CAP} , and N_{INA} (see corresponding text for their definition) with p in a channel of $L = 200 \mu\text{m}$ and $W = 100 \mu\text{m}$. Each data point is obtained by averaging over 1000 independent Monte Carlo samples.

was applied using an Agilent 4284A LCR meter to the gate electrode (i.e., Si substrate), while the S and D electrodes were both set to ground. Pulsed V_{GS} method was employed for both C - V and I - V measurements in order to effectively suppress the adverse effects of charge traps. The interval between two consecutive pulses was set to 10 s since the characteristic time for charge detrapping is ~ 8 s [10]. All the electrical characterizations were carried out under ambient conditions.

III. RESULTS AND DISCUSSION

The percolation behavior of SWCNT networks is depicted in Fig. 1(b). The results are obtained using Monte Carlo simulation [5] with $1.5\text{-}\mu\text{m}$ -long sticks randomly distributed in a channel region $L = 200 \mu\text{m}$ long and $W = 100 \mu\text{m}$ wide. As expected, the total number of SWCNTs N_{TOT} linearly increases with p . The number of SWCNTs forming percolation paths and, hence, carrying current between S and D, N_{PER} , rises sharply from zero when p is greater than p_c . These SWCNTs are active for conducting current as well as for contributing to C_G . There is another class of SWCNTs, denoted N_{INA} , that do not percolate but are still connected to the S/D electrodes or the percolation pathways. These SWCNTs contribute to C_G but not to current conduction. They are slightly most populous below p_c , but overall, they only constitute a rather insignificant fraction of N_{TOT} . Thus, C_G presents a good approximation of the capacitance corresponding to current conduction since the sum of N_{PER} and N_{INA} , yielding N_{CAP} , determines C_G , and the development of N_{PER} with p indeed closely follows that for N_{CAP} in Fig. 1(b). For p near and below p_c , N_{CAP} and N_{PER} differ significantly from N_{TOT} . Most of the SWCNTs remain electrically inactive. The difference between N_{CAP}/N_{PER} and N_{TOT} rapidly disappears with increasing p above p_c , and now, the majority of SWCNTs resides in the percolating pathways.

The transfer characteristics of SWCNT-network TFTs with different p measured by sweeping the gate bias V_{GS} from +40 to -40 V at a fixed drain bias $V_{DS} = -1$ V are shown in Fig. 2(a). A nonpercolated network with $p = 1.8$ gives rise to no conduction current, i.e., I_{DS} at noise level. For TFTs with percolated networks, the ON-state resistance R_{ON} measured at $V_{GS} = -40$ V and the ON/OFF current ratio, I_{ON}/I_{OFF} , decrease with increasing p , cf. Fig. 2(b). For the SWCNT densities of interest here, the intertube resistance predominates,

Fig. 2. (a) Transfer characteristics of SWCNT-network TFTs at different p with pulsed V_{GS} sweeping from +40 to -40 V and $V_{DS} = -1$ V, and (b) (Blue squares) R_{ON} (at $V_{GS} = -40$ V) and (black triangles) I_{ON}/I_{OFF} as a function of p .

and the contact resistance between the SWCNTs and the metal electrodes is of less importance [11]. By referring to the different percolation domains of SWCNT networks [5], the strong dependence of R_{ON} on p reflects the percolation transport in the network, and the large I_{ON}/I_{OFF} near p_c likely implies the formation of mixed percolation paths by both metallic (m -) and semiconducting (s -) SWCNTs or those by s -SWCNTs alone. The rapid reduction of R_{ON} and I_{ON}/I_{OFF} at and above $p = 9.9$ is likely caused by the onset of m -SWCNT percolation [5], [12], [13].

The employment of pulsed- V_{GS} C - V measurement assures an identical flatband voltage for TFTs with different p due to the suppression of adverse effects of charge traps. For TFTs with low-density networks, e.g., $p = 1.8$, the total capacitance measured is, within resolution limits, identical to that of the S/D contact electrodes alone ($p = 0$). For a percolated film with $p \geq p_c$, a net capacitance becomes determinable by subtracting the contribution of the S/D electrodes from the total capacitance.

After removal of the capacitance contribution of the S/D electrodes, the C - V curves measured with V_{GS} from +40 to -40 V and at different f_m are shown in Fig. 3(a) for the TFT with $p = 6.5$. When V_{GS} is negative, holes are accumulated, and the capacitance stays at a high plateau. The capacitance drops when V_{GS} moves toward the positive direction. Normally, the capacitance in depletion is about 1/3 of that in accumulation for SWCNT networks on a 30-nm-thick SiO_2 gate dielectric layer [14]. A thicker SiO_2 as used in this letter (150 nm) would result in a smaller capacitance difference. However, the capacitance difference is much larger, and in depletion, it is only about 1/10 of that in accumulation in our case. This behavior cannot be explained by considering the model with a series connection of C_G with the nanotube quantum capacitance [1] and is instead attributed to the TL effect to be discussed hereinafter. It is noticed, however, that the capacitance does not increase at positive V_{GS} at which inversion in the channel should occur. Such an increase is expected for an ordinary MOSFET [7] and has been shown for TFTs with individual SWCNTs [8]. The high-electron Schottky barrier between the Pd electrodes and the SWCNTs is, hence, suggested to be the hindrance for electron injection into the SWCNT-network channel. This interpretation is supported by the unipolar p -type transfer characteristics of such TFTs as shown in Fig. 2(a).

The accumulation capacitance C_A measured at $V_{GS} = -40$ V for the TFT with $p = 6.5$ stays around 2.2 pF when f_m is below 2 kHz. It decreases continuously and quickly with increasing f_m . Such a strong frequency dependence of C_A is observed for all TFTs with different p as shown in Fig. 3(b). It is clearly seen that C_A stays constant at low f_m

Fig. 3. (a) C - V curves for the TFT with $p = 6.5$ at different f_m with pulsed V_{GS} from +40 to -40 V. (b) Frequency dependence of accumulation capacitance C_A extracted at $V_{GS} = -40$ V for five TFTs with different p . The green dashed line has a slope of -0.5 . (c) C - V curves for the TFTs with different p at $f_m < f_c$ so that the TL effect is absent in accumulation. (d) Measured C_G in accumulation obtained at $V_{GS} = -40$ V in (c), in comparison to (horizontal dashed line) the parallel-plate capacitance C_P . Inset: Excellent agreement between (black open triangles) calculated and (blue solid circles) measured f_c .

and starts to drop (i.e., occurrence of frequency dispersion) over a critical frequency f_c . The results in Fig. 3(b) further indicate that f_c increases with increasing p . For $p \sim 6.5$ at which the percolation is likely to be dominated by s - and m -SWCNTs in mixed mode or s -SWCNTs alone, f_c is ~ 5 kHz. Once m -SWCNTs alone starts to percolate at high p , f_c quickly increases to tens and even hundreds of kilohertz.

To quantitatively analyze the dispersion, the SWCNT networks were treated using an RC TL model with R as the dc resistance and C as the electrostatic capacitance [9]. The discrete elements over the gate length (L) are the resistance per length $r = R/L$ and the capacitance per length $c = C/L$. From the basic TL theory, the attenuation constant can be expressed as $\alpha = (\pi f_m r c)^{1/2}$. Thus, the charging voltage along the tubes drops exponentially with distance at a rate determined by α . By letting the characteristic delay length $1/\alpha$ equal to L , $f_c = 1/(\pi RC)$ is obtained. Above f_c , the channel charging effects cannot be neglected. The log-log plot in Fig. 3(b) shows that the slope of C_A above f_c is indeed ~ -0.5 , i.e., $C \propto f_m^{-1/2}$, confirming the validity of the TL model. It is, therefore, straightforward to expect that the influence of TL effects on the capacitance in depletion will be much more profound due to a higher channel resistance. As a result, a substantial capacitance difference between accumulation and depletion is observed in Fig. 3(a).

By appropriately choosing f_m in order to assure $f_m < f_c$ so that the channel charging is sufficiently fast, the C - V curves for the TFTs with different p were obtained and are shown in Fig. 3(c). The C - V curves shift downward with decreasing p , as expected. As shown in Fig. 3(d), the measured C_G , which is currently in the absence of TL effects, is considerably smaller than what the parallel-plate capacitor model would predict, i.e., C_P . In consistency with the reported simulation results [2], [4], C_A increases continuously and approaches C_P with increasing p . The effective area of the SWCNT networks can be estimated by the ratio C_G/C_P . For a sufficiently dense film, C_G/C_P is

close to one, and the extracted mobility via C_P should, thus, be close to that obtained by using an MIS structure [3]. For a film with p around p_c , $C_G/C_P < 1$ and, consequently, the extracted mobility via C_P would be severely underestimated. For TFTs with percolated SWCNT networks, f_c is calculated by employing the RC TL model with the measured R_{ON} and C_G . As shown in the inset of Fig. 3(d), the calculated f_c (black open triangles) coincides well with its measurement counterpart (blue solid circles). The result once again corroborates the validity of the TL model for TFTs based on SWCNT networks. It is, therefore, critical to obtain capacitance values in the absence of channel charging effects.

IV. CONCLUSION

We have systematically investigated the C_G of SWCNT-network-based TFTs. By employing a well-established characterization method for MOSFETs, it is found that the SWCNTs responsible for current conduction constitute the absolute majority of those contributing to C_G . A strong correlation between SWCNT density and C_G is established with an anticipated low C_G for low density. We have further studied the frequency dispersion of C_G by employing the RC TL model. Measurement of C_G in the absence of channel charging effects has then been achieved, which is crucial for a reliable extraction of carrier mobility. These results can provide useful guidelines for nanoparticle-based TFTs.

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