Faculty and Staff Publication:

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Citation for Final Published Work:

Hu, Z., Tulevski, G. S., Hannon, J. B., Afzali, A., Liehr, M., & Park, H. (2015). Variability and reliability analysis in self-assembled multichannel carbon nanotube field-effect transistors. *Applied Physics Letters*, 106, 243106. doi:10.1063/1.4922770

<http://aip.scitation.org/doi/full/10.1063/1.4922770>

Variability and reliability analysis in self-assembled multichannel carbon nanotube field-effect transistors

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(Received 1 April 2015; accepted 7 June 2015; published online 16 June 2015)

Carbon nanotubes (CNTs) have been widely studied as a channel material of scaled transistors for high-speed and low-power logic applications. In order to have sufficient drive current, it is widely assumed that CNT-based logic devices will have multiple CNTs in each channel. Understanding the effects of the number of CNTs on device performance can aid in the design of CNT field-effect transistors (CNTFETs). We have fabricated multi-CNT-channel CNTFETs with an 80-nm channel length using precise self-assembly methods. We describe compact statistical models and Monte Carlo simulations to analyze failure probability and the variability of the on-state current and threshold voltage. The results show that multichannel CNTFETs are more resilient to process variation and random environmental fluctuations than single-CNT devices. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4922770>]

With continued scaling, silicon-based metal oxide semiconductor field-effect transistors (MOSFETs) are fast approaching their physical limits in sub-10-nm scale regime.^{1,2} The major bottlenecks are the short-channel effects and the inability to reduce the operation voltage.³ In recent years, there has been a drive to explore new channel materials that can conceivably extend conventional device scaling. Due to their small diameter and excellent transport properties, single-walled carbon nanotubes (CNTs) are a particularly attractive candidate.⁴ While serious integration challenges remain, recent successes with gate-all-around geometries and sub-10-nm channel lengths are extremely encouraging.^{5–7} Although the progress is impressive, the remaining technological barriers and process variation, including difficulty in assembling CNTs with a controlled pitch, imperfect semiconducting purity, on-state current (I_{on}) variation, threshold voltage (V_t) variation,⁸ and contact resistance,⁹ still limit the performance. For practical applications in integrated circuits, each transistor must contain multiple CNTs in parallel in order to drive enough on-state current for high-speed switching as illustrated in Fig. 1(a). Multichannel CNT field-effect transistors (CNTFETs) are thus the logical choice for CNT-based circuit design, both due to their increased current and also potentially for the statistical averaging which mitigates the inherent variation between CNTs. Although theoretical studies on the electrical properties of CNT arrays^{10–12} and high-density integration of CNTs have been reported,^{13,14} the effect of the channel number on the performance has not been systematically investigated.

In this work, we fabricated thousands (~3000) of multichannel CNTFETs with four different numbers of CNT-channels. The CNTs were individually placed on

patterned oxides by using ion-exchange chemistry and patterned oxides.¹³ Our CNT assembly method is illustrated in Fig. 1(b). Hafnium oxide (HfO₂) trenches were formed by patterning SiO₂ (thickness = 7 nm) on a uniform HfO₂ film (thickness = 10 nm). The number of trenches is equivalent to the number of CNT channels since most of trenches contain a single CNT. Trench array patterns with a width/pitch of 100/500 nm were written by electron-beam lithography (EBL), followed by SiO₂ evaporation and lift-off in acetone. Immediately before monolayer deposition, the substrates were cleaned in oxygen plasma (0.6 Torr, 5 min) to remove hydrocarbon residuals. Then, the patterned substrate was immersed in a 3.5 mM solution (3:1 ethanol/water) of 4-(N-hydroxycarboxamido)-1-methylpyridinium iodide (NMPI) for 1 h, followed by rinsing off excess NMPI by ethanol. The NMPI containing a hydroxamic acid group selectively binds to the HfO₂ surface but does not stick to SiO₂.^{13,15} An aqueous CNT solution in SDS with a high semiconducting purity was prepared via column chromatography¹⁶ and was applied on the patterned substrate for 1 h. The iodide of NMPI was exchanged with the anionic surfactant wrapped around CNTs, leading to a strong coulombic attraction between the negatively charged CNTs and the positively charged monolayer. This process results in deposition of the CNTs in the HfO₂ trenches, but not onto the SiO₂ field oxide. After rinsing, the substrate was annealed in vacuum to decompose the monolayer and remove the surfactant. The source and drain electrodes (Ti/Pd/Au = 0.5/20/20 nm) were fabricated by using EBL, metal deposition, and lift-off. HMDS coating was applied on the devices right before carrying out the electrical measurements in a semi-automated probe station (Cascade summit) in air. The highly doped silicon substrate was used as a backgate to modulate the CNT channel.

A scanning electron microscope (SEM) image in Fig. 1(c) shows the channel region of a multichannel CNTFET with 6 HfO₂-trenches on which CNTs were

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FIG. 1. Schematic of (a) a scaled multichannel CNTFET for sub-10-nm node logic application and (b) CNT placement method based on ion-exchange chemistry. (c) SEM image of the channel region of 6-channel CNTFET (scale bar: 200 nm). (d)–(g) V_g - I_d curves of 370 randomly selected devices each for 1-CNT-channel, 2-CNT-channel, 4-CNT-channel, and 6-CNT-channel CNTFETs, respectively.

selectively assembled. About 3000 devices with different channel numbers were fabricated on a single chip and electrically measured, out of which 370 subthreshold curves (plot of the drain current versus gate voltage) for each channel number (1, 2, 4, and 6) were randomly selected for statistical analysis. Comparing the subthreshold curves in Figs. 1(d)–1(g) provides valuable insights into the effect of the channel number on the performance of CNTFETs. The subthreshold curves of these devices shift towards higher current levels as the channel number increases, while the variation in the current is reduced. This general dependence of performance on the channel number can be analyzed quantitatively, as we show below.

Several imperfections of the manufacturing process, such as non-ideal self-assembly of CNTs and the presence of a small fraction of metallic CNTs, complicate the analysis. A model that takes into account the yield and purity is needed to analyze the data precisely. First, we considered the effect of CNT placement yield that is defined as t_k , the probability that a given channel contains k CNTs. Ideally, $t_1 = 1$ with all other $t_k = 0$, corresponding to the case where CNTs will only adhere in “empty” trenches. Here, the number of trenches is equivalent to the number of channels of CNTFETs. However, previous analysis shows that this is not the case.¹³ Specifically, direct imaging of CNT placement with SEM suggests $t_1 : t_2 : t_3 = 9:3:1$, $t_0 + t_1 + t_2 + t_3 = 1 - \varepsilon$, where t_k is the probability of having k CNTs in one trench and ε is the fabrication defects rate. A well-behaved switching multichannel CNTFET requires all the channels contain

semiconducting CNT only. Thus, the probability of a multichannel CNTFET being a switching device (i.e., having no metallic CNTs) ($\hat{p}_n$) can be written as by

$$\hat{p}_n = \begin{cases} \frac{t_1 p + t_2 p^2 + t_3 p^3}{t_1 + t_2 + t_3}, & 1\text{-channel CNTFET}, n = 1 \\ p^{(t_1 + 2t_2 + 3t_3)n}, & n\text{-channel CNTFET}, n > 1, \end{cases} \quad (1)$$

where p is the semiconducting CNT purity. The expected connection yield is given by $1 - \varepsilon - t_0^n$. This number is the fraction of devices that contain at least one CNT. The effective number of CNTs (k_{eff}) for an n -channel CNTFET can thus be derived to be

$$n_{eff} = \frac{k(1 - \varepsilon - t_0)(t_1 + 2t_2 + 3t_3)}{(1 - \varepsilon - t_0^n)}. \quad (2)$$

The calculated effective CNT numbers are shown in Fig. 2, which are used as the channel numbers in the calibrated data shown in Figs. 3(b) and 3(c) and Figs. 4(c) and 4(d).

As shown in Fig. 2, the connection yield increases from 85% for 1-channel CNTFETs to above 98% for multichannel CNTFETs. The expected connection yields of multichannel CNTFETs should approach 100%; however, 100% yield was not obtained in our 6-channel CNTFETs due to fabrication defects such as the failure in SiO₂ and metal lift-off processes. The percentage of switching devices decreases as multichannel CNTFETs have a higher probability of containing at least one metallic CNT. The predicted percentage of

FIG. 2. Statistical analysis of connection and switching device yield of multichannel CNTFETs.

switching devices by Eq. (1) agrees well with the experiment data. We thus can conclude that the major causes of failure in multichannel CNTFET are “shorts” due to the presence of metallic CNTs. For instance, for the process conditions used in this work, we find that the 2-channel CNTFET has the lowest failure probability, and further that the semiconducting CNT purity has to be higher than 99.86% to maintain a low failure probability ($<1\%$) for a 6-channel CNTFET.

In Fig. 2, the semiconducting CNT purities derived from Eq. (1) are consistently in the range of 93%–96% for single-channel and all multichannel CNTFETs, which in turns validates the above analysis. We note that electrical analysis of multichannel CNTFETs can be used to efficiently determine the purity of ultra-pure CNT solutions as an n -channel CNTFET has a much larger probability ($1 - p^n$) to catch rarely presented metallic CNT in a high purity solution than that of a single-channel CNTFET ($1 - p$).

We first analyzed the performance of I_{on} for multichannel CNTFET as shown in Fig. 3(a). We extracted I_{on} under identical V_g (-3 V) and V_d (0.5 V), so this analysis includes contributions from V_t variation, contact resistance, and CNT diameter variations. The dependence of mean $\mu(I_{on})$ and normalized standard deviation $\sigma(I_{on})/\mu(I_{on})$ on the channel number was also evaluated with Monte Carlo simulations. In the simulation, the V_g - I_d curve corresponding to each n -channel device sample was generated by summing up n subthreshold curves randomly selected from the pool of 370 experimental curves of single-channel CNTFETs. The final simulated $\mu(I_{on})$ and $\sigma(I_{on})/\mu(I_{on})$ were obtained from 50 000 simulations. As shown in Figs. 3(b) and 3(c), the slope of the simulated results agrees well with the experiment data. But it slightly deviates from the n scaling rule for $\mu(I_{on})$ and $1/\sqrt{n}$ scaling rule⁸ for $\sigma(I_{on})/\mu(I_{on})$ which are based on the assumption of the ideal connection yield (100%). This discrepancy can be attributed to the imperfect connection yield (85%) seen in the experimental data as well as used in the simulation. This result clearly shows that I_{on} increases with the number of CNT-channels, but that the increase was not ideal, i.e., proportional to n , due to imperfect CNT placement yield.

In this study, we defined V_t as the gate voltage corresponding to a subthreshold current I_d of 100 nA. For this

FIG. 3. Comparison of the on-state current (I_{on}) measured under identical bias condition ($V_g = -3$ V and $V_d = 0.5$ V). (a) The distribution plot of I_{on} for multichannel CNTFETs. (b) Change of the average on-state current [$\mu(I_{on})$] as a function of the channel number n . (c) Change of the normalized standard deviation of the on-state current [$\sigma(I_{on})/\mu(I_{on})$] as a function of the channel number n . The on-state current level increases and its variation decreases as the channel number increases.

current level, channel resistance dominates and the contact resistance has less impact.¹⁷ The measured V_t values for single-channel and three types of multichannel CNTFETs are plotted in Fig. 4(a), in which the V_t distribution of the single-channel CNTFETs approximately follows a normal distribution. The experiment results show that the average threshold voltage [$\mu(V_t)$] of multichannel CNTFETs increase with n while the standard deviation of V_t [$\sigma(V_t)$] decreases with n in Figs. 4(c) and 4(d), respectively. The reduced variation of I_{on} and V_t implies that the device performance variation caused by the variation of CNT diameters, environment

FIG. 4. Comparison of the measured threshold voltage (V_t) corresponding to the identical subthreshold current of 100 nA. (a) The distribution plots of measured V_t values for single-channel and multichannel CNTFETs (370 devices for each device type). (b) The probability density functions of V_t of multichannel CNTFETs based on the proposed model. (c) Change of the average threshold voltage [$\mu(V_t)$] as a function of the channel number n . (d) Decrease of $\sigma(V_t)$ as a function of the channel number n .

(such as charges on the substrate), and process variation can be reduced by the multichannel design.

The scaling of V_t as a function of the channel number was shown to be less effective than $1/\sqrt{n}$ scaling rule.⁸ We propose a statistical model given by Eq. (3) to describe the distribution of V_t of multichannel CNTFETs, by simply assuming that V_t for a p-type (n-type) multichannel CNTFET is determined by the CNT channel with the most positive (negative) V_t (Ref. 18)

$$f(V_t|\mu, \sigma) = \frac{n}{\sigma} \phi\left(\frac{V_t - \mu}{\sigma}\right) \left[\int_{-\infty}^{V_t} \frac{1}{\sigma} \phi\left(\frac{t - \mu}{\sigma}\right) dt \right]^{n-1}, \quad (3)$$

$$\phi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2}.$$

This statistical model quantitatively predicts the change of $\mu(V_t)$ and $\sigma(V_t)$ as a function of n . The probability density functions of V_t of 1-, 2-, 4-, and 6-channel CNTFETs are plotted in Fig. 4(b). The trends are also confirmed by Monte Carlo simulation which was carried out by the same process used for the on-state current simulation. The noticeable shift between the model and the experiment results in V_t is probably caused by an additional V_t shift that comes from uncontrolled environmental factors between each measurement for different device sets. The experimental results and the modeling clearly indicate that the multichannel design can reduce the threshold voltage variation, which is one of the most critical issues with CNTFETs. In this work, the model tends to underestimate the reduction of V_t variation with increasing channel numbers. A possible reason is that the variation of subthreshold slope in experiment is not included in the simple V_t determination method of the model.

In summary, we have systematically investigated the effect of the number of CNTFET channels on the performance of multi-CNT devices by fabricating and measuring a large number of multichannel CNTFETs on a single chip. This study shows that the on-state current can be increased and the threshold voltage variation can be reduced by increasing the number of channels in CNTFETs. For our process conditions, increasing the channel number from 1 to 6 increases I_{on} by a factor of 5 and reduces variations of I_{on} and V_t by a factor of 2. However, our results also indicate that the major failure mode in the scaled multichannel CNTFETs will be the “shorts” caused by metallic CNTs. This work shows that the fabrication and evaluation of a large number of multi-CNT-channel transistors can give important and useful insight into CNT circuit design.

The authors thank J. Bucchignano and S. Dawes for technical assistance with electron-beam lithography and S.-J. Han for helpful discussions. H.P. acknowledges the financial support from the BK21 Plus project funded by the Ministry of Education, Korea (21A20131600011).

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