Radio Frequency Nanoelectronics Based on Carbon Nanotubes

Nima Rouhi, Dheeraj Jain, Peter John Burke

Electrical Engineering and Computer Science Department, University of California, Irvine, CA 92697, U.S.A.

Abstract — **Many studies have suggested the potential applications of carbon nanotubes (CNT) in conventional analogue radiofrequency (RF) technology. This is due in part to near-ballistic electron transport and expected high frequency performance. In this paper, we will present the latest understanding of the potential applications of nanotubes in this broad application area.**

Index Terms — **carbon nanotube, large-scale application, printed circuits, radio frequency, semiconducting film.**

I. INTRODUCTION

Semiconductor device technology is focusing on fabricating smaller, faster and lower power consuming devices. There have been extensive research efforts during the past decade to find materials and demonstrate their electrical properties to help downscaling the device dimension while maintaining and/or improving their functionalities. Carbon nanotubes and graphene are known as potential candidates to replace and/or integrate with current silicon technology. This is due to near-ballistic electron transport, very small size (1 nm or less), high current carrying capacity, and high projected cut-off frequency.

A single-walled carbon nanotube (SWNT) is a sheet of graphene (sp^2 carbon honeycomb lattice) rolled up into a seamless cylindrical shape. Based on the cut and degree of twist in the graphene sheet, SWNTs can show either metallic or semiconducting behavior. Owing to this unique characteristic, carbon nanotubes have shown a great potential in different electronic applications including transistors and RF devices, digital logic circuits, interconnects and conductive sheets[1]. Individual SWNTs are known to have mobility of about 10,000 cm^2/V-s, which is an order of magnitude more than that of silicon. Besides, the cut-off frequency of SWNT is predicted to enter the THz regime, while experimentally it has not yet passed 100 GHz. The critical milestone from the fabrication part is to obtain purified semiconducting nanotubes and control the alignment degree of the deposited carbon nanotubes. Recent works demonstrate the ability of carbon nanotube-based systems such as antennas, mixers and amplifiers [1]. The key concern is the timeline for carbon nanotube based nanoelectronics from prototypes to manufacturing capability.

Several approaches have been tried to demonstrate different fabrication techniques for depositing nanotubes at preferred locations to be able to obtain high performance nanotube-based circuits. Based on the process, these different approaches can be divided into two major pathways; “grow-in-place” and “solution-based (nanotube ink)”. While the “grow-in-place” method suffers from lack of control over the chirality (therefore electrical properties) of the nanotubes network, “nanotube inks” show a great potential for nanoelectronics and especially printed electronic devices, as well as heterogeneous integration with digital CMOS. Therefore, it is highly desirable to establish a method to design, fabricate, and control the performance of nanotube device in a scalable process. In order to achieve this goal, a thorough understanding of the performance projections of nanotube inks is critical, specifically regarding manufacturing yield, reproducibility, cost management, and optimized performance (such as mobility, on/off ratio, transconductance, high frequency, etc.).

The prospect of using nanotube inks for a variety of applications including printed circuits and flexible electronics has recently entered a new level, as techniques to purify semiconducting nanotubes from mixtures were recently developed. It has been recently shown that it is feasible to control the performance of transistors for a broad spectrum of applications from printed digital circuits such as inverter, nand, nor, etc. to RFID tags [2, 3]. However, one of the main concerns is the cost of such purified nanotube inks. In spite of that, this technology is promising for the printed nanoelectronic technology based on primary results.

The purpose of this article is to study the possibilities of carbon nanotube based electronics. The most up to date progress in the field has been discussed here, including more recent additions since our prior review[1]. In addition, the potential future prospects are also introduced based on results presented in this paper.

II. CONVENTIONAL TECHNOLOGY AND CARBON NANOTUBE

Carbon nanotubes are interesting candidates for several potential analog RF applications[1, 4, 5]. In addition to the frequency response of nanotube-based devices, mobility and on/off ratio are two important figures of merit to evaluate the performance of active devices. Fig. 1 shows the mobility trend in the past decade for different semiconductor device technologies.

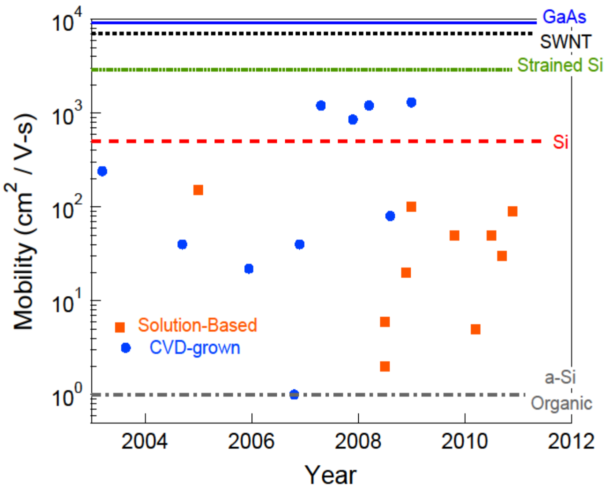

Fig. 1. Mobility vs. Year for both Solution-based and CVD-grown nanotube devices (orange squares represent solution-based and circles represent CVD-grown nanotube devices) compared to conventional field effect and thin film transistors [1-3].

Individual single-walled carbon nanotubs are known to have a high mobility of around 10000 cm^2/V-s. However, using a random network of carbon nanotube results in degradation in mobility of transistors. CVD-grown (blue circles in Fig. 1) and solution-processed (orange squares in Fig. 1) nanotube thin film transistors (TFTs) are also presented here. Recent reports demonstrate great improvement in the mobility of purified nanotube ink TFTs [2, 3]. CVD-grown aligned nanotubes on quartz substrates show high mobilities (around 10^3) but low on/off ratios [3, 6]. In addition, CNT based transistors show higher mobility than common α-Si or organic-based printed electronics. Recently improved techniques in semiconducting carbon nanotube TFTs show more than 100X increase in mobility compared to organic TFTs while the on/off ratio is still high enough [2].

Individual carbon nanotube devices have predicted THz cutoff frequencies[1, 4], but practicalities of parasitic capacitances have limited so far the experimental results to demonstrate *intrinsic* cut-off frequencies (f_t) of not more than 80 GHz with an *extrinsic* f_t of around 15 GHz [4, 7]. The maximum gain frequency (the maximum frequency of oscillation, f_{max}) is also deducted to be 3 GHz, which is smaller than f_t in this case. For short channel devices, f_t has an inverse relationship with the channel length as shown here

$$f_t = \frac{\upsilon_{sat}}{2\pi L_g} \qquad (1)$$

whereas for long channel devices it depends on both the channel length and mobility

$$f_t = \frac{\mu(V_g - V_t)}{2\pi {L_g}^2} \qquad (2)$$

Therefore, it is critical to control the mobility and channel length especially for current printing techniques which mostly produce long channel devices. To control mobility it has been shown recently that nanotube network density is a key parameter [2, 3]. Increasing the network density will increase the mobility. On the other hand, it increases the probability of having metallic tubes in the channel (since so far there is no 100% pure semiconducting nanotube ink available) and that decreases the on/off ratio. Consequently, there exists a tradeoff between mobility and on/off ratio that has been discussed in detail in [2, 3]. Fig. 2 shows schematic of printed RF transistors on flexible substrate.

III. System Demonstration

Considering all above research studies, there has been no commercial demonstration of printed nanotube networks to fabricate a genuine nanoelectronic system until recently where a research group in Korea presented the first RFID tag on flexible substrate using roll-to-roll all-printed carbon nanotube circuit [4, 8].

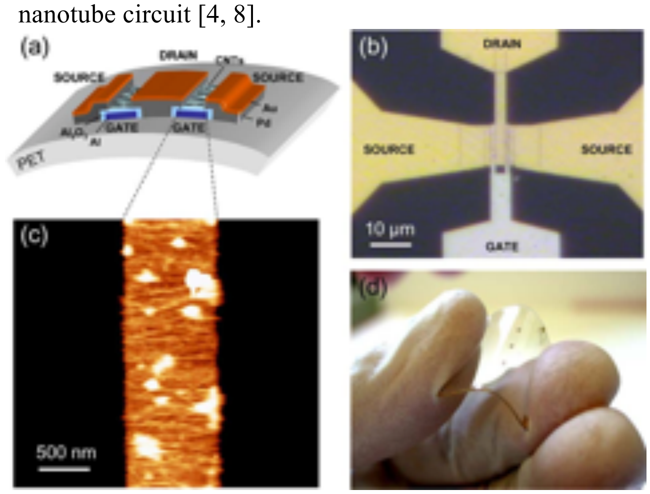

Fig. 2. a) Schematic of device on plastic substrate. b) Optical image of fabricated device with final electrodes. c) Atomic Force Microscopy (AFM) image of the nanotube channel, aligned nanotubes deposited using Dielectrophoresis (DEP) technique. d) Optical picture of final devices on plastic substrate [9].

Their all-printed and R2R-printable 13.56 MHz 1-bit tags contains a rectifier that can provide at least 10 V dc at 13.56

MHz coupled ac from the reader and a ring oscillator that can generate a stable 100 Hz clock signal by the dc power generated from the rectifier. The 1-bit RF tag would completely be printed in three steps: 1) antenna, electrodes, gate electrodes, and gate dielectrics were R2R gravure printed on plastic foils 2) the ring oscillator to generate clock signals under 10 V dc was added; and 3) a rectifier to yield 10 V dc at 13.56 MHz ac was added.

The printed 1-bit RF tag reveals a great potential in the area of large-scale printed RF nanotechnology based on carbon nanotubes. However, their fabricated devices suffer from low mobility and low on/off ratio, which are two important parameters in switching speed and power consumption of the devices, respectively. The highest mobility reported in this work was ~5.5 cm^2/V-s while the on/off ratio of that device was around 100. On the other hand the highest on/off ratio, 10^3, belongs to a device with the mobility as low as 1 cm^2/V-s and that is not appropriate for high speed and high current carrying circuits.

Looking into the first nanotube-based printed RFID tag, it is also worth to mention that printed sub-3 V digital circuit have also been fabricated using purified 98% semiconducting nanotube ink [3]. Here they are offering basic digital circuits such as inverter, NAND gate, and ring oscillator on both polyimide and SiO_2 substrate. The semiconducting carbon nanotube network and high capacitance ion gel gate dielectric is patterned by jet printing of liquid inks. Printing was accomplished in ambient conditions using a commercially available aerosol jet printing system. The water-based CNT ink was printed on the channel area with a printing speed of 3 mm/s (5 mm/s for low-coverage films). The measurements are also performed in vacuum due to sensitivity of the gel electrolyte (used as dielectric) to moisture. Considering the vacuum environment and long-run process of fabricating the logic gates, their technique requires more investigations to be feasible for large-scale printed circuits. The highest mobility of their devices is in the range of 50 cm^2/V-s for high-density nanotube film on SiO_2 substrate, while the highest on/off ratio is 10^3~10^4. Here, five-stage ring oscillators achieve frequencies above 2 KHz at the supply voltage of 2.5 V corresponding to the delay times of 50 μs.

V. Prospects

In previous sections some demonstrations of solution-based nanotube circuits in DC and high frequency range (~80 GHz) has been presented. Although, the intrinsic radio frequency characteristic of individual and random network of nanotube has been explored showing the capability of exceeding the 80 GHz boundaries (and 1 THz theoretically), the optimization of such radio frequency devices for solution-based random network of nanotubes is yet not clearly discovered. The main question is the limits for such random network of semiconducting nanotubes.

While carbon nanotube inks show promising future applications in nanoelectronics, one of the main disadvantages of such inks is the process by which the nanotube solution is purified. Mainly these processes involve high-power ultracentrifugation and acid treatments. This may result in reduction of nanotube length and degradation in their electrical performance. Further investigations to improve the purification techniques are required for achieving high performance nanotube ink-based electronics.

Furthermore, to date, very few demonstrations of RF applications for solution-based purified 99% semiconducting inks have been presented [3, 4]. The cut-off frequency (f_t) is extracted from S-parameters with de-embedding techniques. However, the actual device works under the parasitic influences of fringing, gate-source and gate-drain overlap capacitances, etc. Hence the extrinsic cut-off frequency will be more realistic in application while the intrinsic cut-off frequency (after de-embedding) represents the ultimate potential of the device's performance. As mentioned above, the extrinsic and intrinsic cut-off frequencies obtained from 99% solution-based random network transistors with sub-micron (300 nm) channel length are ~15 GHz and 80 GHz respectively.

In Fig. 3 we present a comprehensive survey of mobility and on/off ratio for all published results of purified and non-purified nanotube ink. This represents the collective knowledge to date of the relationship between mobility and on/off ratio for nanotube inks, and forms an important roadmap for the future of the field.

As shown here for purified inks, mobility decreases to less than 10 as the on/off ratio increases to 10^6. This can be explained by the existence of metallic tubes since yet there is not 100% semiconducting nanotube ink available. Although all the blue points in this figure use purified nanotube inks, but the purification method and percentage (ratio of metallic to semiconducting), deposition techniques (drop-dry, spin-coating, DEP, etc.) and fabrication steps vary from one to another, which should be considered as well. Furthermore, it can be seen in Fig. 3 that regardless of the technique, for <100% purified nanotube inks, the fabricated transistors follow the same trend. On the other hand, for the non-purified solution-based devices, the trend is considered to be different. It can be seen from this figure that there is a drastic drop in mobility as the on/off ratio goes up. To obtain low on/off ratio for non-purified techniques, mostly the nanotube network is around or below the percolating threshold to suppress the effect of metallic tubes on the on/off ratio. Therefore, mobility decreases in most cases.

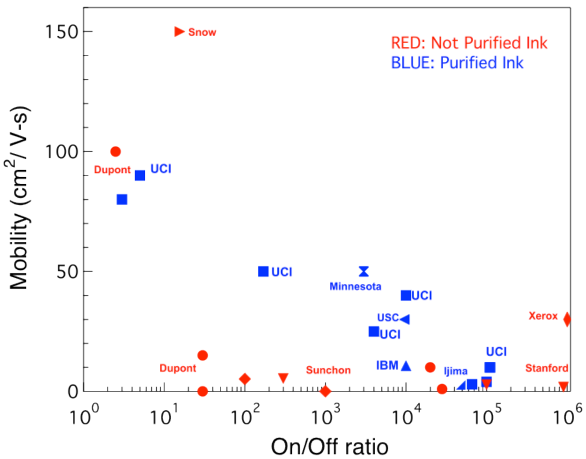

Fig. 3. Mobility vs. On/off ratio for both purified (blue) and non-purified (red) nanotube ink devices, showing an inverse relationship [2, 3].

Although, this work illustrates the potential of random networks of purified semiconducting nanotubes in radio frequency applications, the very small channel lengths required to obtain high frequencies is a critical milestone for available printing techniques. Considering the state-of-the-art nanoelectronic printing methods, the large-scale fabrication of ultra high frequency devices is yet not possible. However, by improving the printing methods in future for sub-micron resolutions, it is likely to fabricate large-scale printed radio frequency circuits. Nevertheless, CNT based devices are promising candidates to revolutionize the high frequency and high performance printed systems in the near future. Needless to note that alignment degree of printed nanotube network is a critical and challenging parameter that should be considered especially for radio frequency printed nanocircuits.

VII. Conclusion

The potentials of carbon nanotube electronics to replace or embedded with the conventional device technologies have been studied here. It has been shown that solution-based random network of semiconducting carbon nanotube is an alternative to as-grown nanotubes to be used in nanoelectronic devices. However, to date, there is no precise numerical analysis of random network of semiconducting nanotube networks. Analytical review of nanotube networks leads to better understanding of various parameters influencing the device's performance such as cut-off frequency, mobility and on/off ratio. It has been shown that to achieve high mobility, high on/off ratio, and high-frequency carbon-based transistors, it is essential to have purified all-semiconducting nanotubes in the channel and control the density and alignment of such network of nanotubes. According to these preliminary results, carbon nanotube ink printed transistors are showing mobility of around 100 cm^2/V-s which is close to that of p-type silicon transistors. These achievements open up the potential future applications for nanotube transistors.

Acknowledgement

The authors wish to acknowledge the assistance and support of the National Science Foundation, the Army Research Office, the Office of Naval Research, Northrop Grumman and the Korean National Science Foundation (KOSEF) World Class University (WCU) program.

References

[1] C. Rutherglen, D. Jain, and P. Burke, "Nanotube Electronics for Radiofrequency Applications," *Nat Nanotechnol,* vol. 4, pp. 811-819, Dec 2009.
[2] N. Rouhi, D. Jain, K. Zand, and P. J. Burke, "Fundamental Limits on the Mobility of Nanotube-Based Semiconducting," *Adv Mater,* vol. 23, pp. 94-99, Jan 4 2011.
[3] N. Rouhi, D. Jain, and P. J. Burke, "High Performance Semiconducting Nanotube Inks: Progress and Prospects," *ACS Nano,* in press, 2011.
[4] N. Rouhi, D. Jain, and P. J. Burke, "Nanoscale Devices for Large-Scale Applications," *IEEE Microwave Magazine,* vol. 11, pp. 72-80, Dec 2010.
[5] P. Russer, N. Fichtner, P. Lugli, W. Porod, J. A. Russer, and H. Yordanov, "Nanoelectronics-Based Integrated Antennas," *IEEE Micr Mag,* vol. 11, pp. 58-71, Dec 2010.
[6] W. W. Zhou, C. Rutherglen, and P. J. Burke, "Wafer Scale Synthesis of Dense Aligned Arrays of Single-Walled Carbon Nanotubes," *Nano Res.,* vol. 1, pp. 158-165, Aug 2008.
[7] H. Happy, L. Nougaret, G. Dambrine, V. Derycke, J. P. Bourgoin, A. A. Green, and M. C. Hersam, "80 Ghz Field-Effect Transistors Produced Using High Purity Semiconducting Single-Walled Carbon Nanotubes," *Appl Phys Lett,* vol. 94, Jun 15 2009.
[8] M. Jung, J. Kim, J. Noh, N. Lim, C. Lim, G. Lee, J. Kim, H. Kang, K. Jung, A. D. Leonard, J. M. Tour, and G. Cho, "All-Printed and Roll-to-Roll-Printable 13.56-Mhz-Operated 1-Bit Rf Tag on Plastic Foils," *IEEE Trans. Electron. Dev.,* vol. 57, pp. 571-580, Mar 2010.
[9] V. Derycke, N. Chimot, M. F. Goffman, J. P. Bourgoin, H. Happy, and G. Dambrine, "Gigahertz Frequency Flexible Carbon Nanotube Transistors," *Appl Phys Lett,* vol. 91, Oct 8 2007.