CNT Based Nano Electro Mechanical Systems (NEMS)

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Abstract:
The paper reports on the development of carbon nanotube based nano electro mechanical sensors.

1. INTRODUCTION

Further system miniaturization will certainly create demands for a continuous down-scaling of sensor functions in a variety of different application fields. Further scaling of transducers in general and sensors in particular, is mandatory for all applications where ultra-miniature size enables the exploration of the nano-cosmos. System biology for example, which is currently taking off as research discipline to explore the basic principles of living systems by quantitative modeling of inter and intra cellular processes [1], will starve for sensors to provide data for model verification. Implantable devices like future autonomous micro robots or multifunctional endoscopes [2] for minimal invasive diagnostics [3], health monitoring [4], drug delivery and many other intra-corporal tasks need ultra-miniature sensors to fulfill their missions while minimizing invasiveness. Last but not least, system miniaturization and device integration, based on reproducible fabrication processes and large scale production, are still the top pre-requisites for low cost products. However, limitations in down-scaling of conventional micro electro mechanical systems (MEMS) are foreseeable [5]. Therefore new materials with new properties on the nano-scale will emerge to fulfill sensor tasks in ultra-miniaturized sensor systems. In this paper, first proposals to create electro mechanical sensors based on carbon nanotubes (CNTs) are discussed.

2. CARBON NANOTUBES AS ELECTRO MECHANICAL TRANSDUCERS

Carbon nanotubes, discovered in 1991 [6], are one of the most intensely studied nanostructures to date [7], [8], [9] and are very promising for the further miniaturization of sensors due to their unique properties. Single wall carbon nanotubes (SWNTs) are hollow cylinders of graphene, composed of a single layer of carbon atoms. The length of the tubes can be several micrometers and the diameters are on the order of 1 nm, owing to very high aspect ratios. Perfect SWNTs without distortions show ballistic conductance and may carry very high current densities (up to 10^9 A/cm^2 [10]). Depending on the chirality, which describes the structural symmetry of the tubes, they can exhibit either metallic or semiconducting behavior. Moreover, they are highly elastic with Young's modulus in the range of 1 TPa [11]. Their extraordinary mechanical, electrical and electro mechanical properties will make them to promising candidates for very sensitive elements in nanosystems. Research on CNTs for transducers is taking off and first realizations of CNT-based nano mechanical systems have been recently published [12], [13], [14]. Some of the many application ideas for utilizing CNTs as structural mechanical elements include data storage [15], relays [16], oscillators [17], [18], switches [19], and sensors [21], [23].

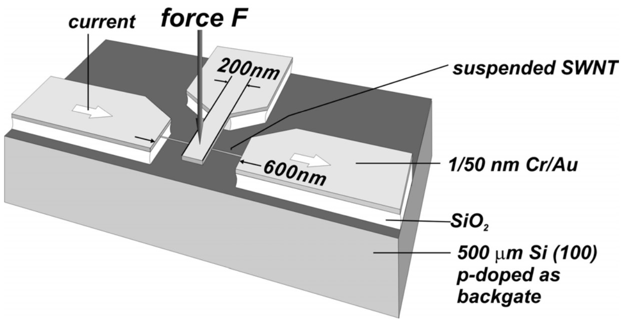
For sensing mechanical units, the electro mechanical properties of SWNTs are of interest. Recent experiments have proven their potential use as piezoresistors in a variety of applications. In a very recent experiment Grow et al. [24] studied the electro mechanical response of semiconducting and small-gap semiconducting SWNTs adhered to a silicon nitride surface. They reported gauge factors from - 376 up to 856 for semiconducting and small-gap semiconducting SWNTs, respectively. In an earlier publication Cao et al. [25] reported effective piezoresistive gauge factors of between 600 and 1000. In the experiment of Tombler et al. [26], an atomic force microscope (AFM) tip was used to deform a SWNT (global strain of 3%). A decrease in conductance of more than two orders of magnitude was observed. The reason for this strong response may be twofold: First, the AFM tip locally deformed the SWNT such that the local bonding configuration changed from sp^2 to nearly sp^3. Such local deformations may appear when a sharp edge kinks the SWNT. Second, away from the edge (i.e. tip) region, the SWNT remained in the sp^2 bonding configuration with a uniform bond deformation characterized by the global strain induced by the deformation. It is not yet fully understood how these two effects interplay to contribute to the overall change in conductance. Theoretical investigations [27] point out that this may strongly depend on the chirality (armchair or zigzag) of the SWNT and on the shape of the AFM-tip or edge. However, both mechanisms are reversible, which is of particular interest from the application point of view. The high elasticity of the covalent carbon-carbon bonds is proposed to allow the SWNT to return, even from a strong deformation to its original state, i.e. symmetric sp^2 bonding configuration. This fact combined with the remarkable electrical response to a mechanical load makes SWNTs promising candidates for novel device concepts.

3. SUSPENDED CARBON NANOTUBE ELECTRO MECHANICAL TRANSDUCERS

For the evaluation of these new device concepts utilizing CNTs as electro mechanical transducers SWNTs have been integrated into MEMS-like structures [28], [29], [30]. These test stands, which are shown in Fig. 1.a, b and c are designed to provide the following features: An individual SWNT is connected to and fixed by electrodes and it is suspended from the substrate (electrodes: 1-2 nm Cr as adhesion layer, 30-50 nm Au as contact material). Force is applied to the tube via a cantilever or bridge structure, which is actuated by an atomic force microscope. This provides a precise mechanical interface to the tube, applying local deformation at the edges and axial strain in the branches of the tubes.

The fabrication technique is based on randomly pre-deposited SWNTs (dispersed in SDS) on a Si/SiO_2 substrate. AFM images are recorded to determine spatial orientation and location of each discrete nanotube. Electron beam (e-beam) lithography is subsequently used to pattern (lift-off) the metallic electrodes for the nanoscale structures. Diluted HF etching followed by critical point drying finalizes the nano device fabrication (Fig. 1.b and c). We use discrete, highly purified and chemically stable CNTs (from CNI, fabricated by an HiPCO process) as active elements to reliable withstand HF release.

The electro mechanical characterization of the structures revealed the following conclusions: The deflection of the 30-50 nm Au structures is well described by simple elastic beam theory (Euler-Bernoulli theory of beams) in the small deflection regime. The SWNT in the given set up contributes significantly to the stiffness of the system (spring constant) and is well described by modelling the tube mechanics like a string. The measurement of the resistance of the SWNTs under mechanical load showed a significant and reversible increase of the tube's resistance in dependence of the deflection of the tube. At zero-deflection the resistances is in the range of 500 kΩ. It then increases to 1 MΩ at a tube deflection of 30 nm (bridge type test stand [29]). Thus the concept of nano electro mechanical systems has been proven.



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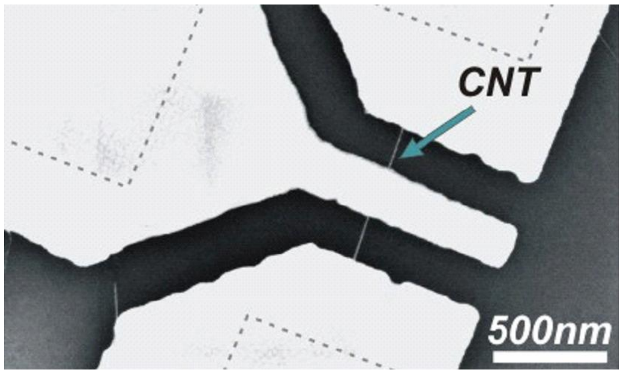

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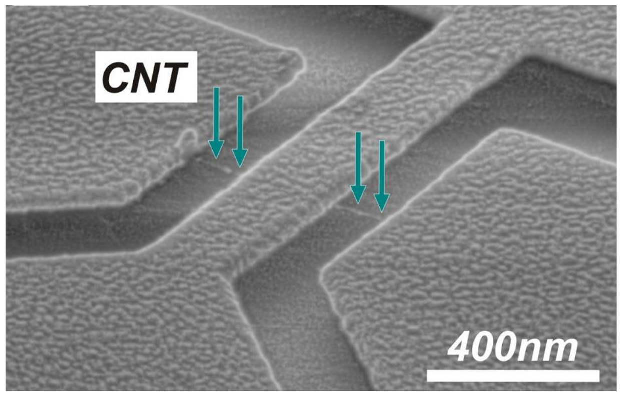


c)

Figure 1: Suspended carbon nanotube electro mechanical transducers.
a) Concept of a functional building block.
b) 50 nm thick Cr/Au cantilever and contact pads with suspended CNT underneath [28].
c) 41 nm thick Cr/Au bridge and contact pads with suspended CNT underneath [29].

4. MEMBRANE BASED CARBON NANOTUBE ELECTRO MECHANICAL TRANSDUCERS

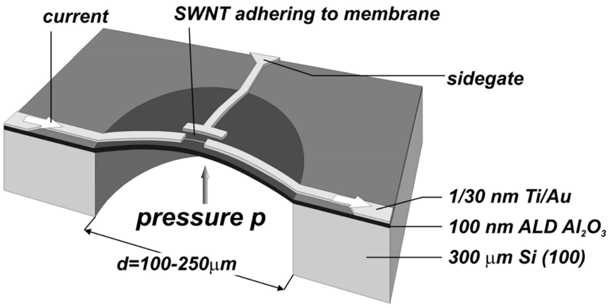
Complementary to the suspended CNT electro-mechanical transducers, which are discussed in section 3, membrane based CNT transducer have been developed [22], [31]. As an advantage of the membrane based test-stands the local deformation of the tube at the edges of the cantilevers or bridges is avoided and axial stress is applied to the tube by straining the membrane. This device is a SWNT pressure sensor, utilizing the tube as electro mechanical piezoresistive transducer (Fig. 2).

Attempts have been made earlier to use the electro-mechanical response of CNTs for pressure sensor applications [20], [21], [24]. These attempts do not fully take advantage of the small size and material properties of the SWNT elements. For example, the pressure sensor described in [20] is made up of a circular PMMA membrane that is 2 mm in diameter and 300 μm in thickness. This is very large compared to the diameter and length of CNTs. Bundles of multi-walled CNTs are connected across the membrane. The measured gauge factor of the CNT bundles is 235 [20]. Similarly, the membrane of the pressure sensor structure described in [24] is composed of 1.15 μm thick, 1.035 mm square silicon nitride membranes where SWNTs were grown from catalyst islands. Then the CNTs were fixed in place with contact electrodes (Pd, device gap: 0.3 – 1 μm). Gauge factors from – 376 up to 856 of small-gap semiconducting and semiconducting SWNTs are reported.

Based on the process flow described in brief above (section 3) and an additional bulk micromachining step to release the ALD (Atomic Layer Deposition) Al_2O_3 membrane, SWNT pressure sensors were fabricated with membrane diameters between 100 μm and 250 μm. Differential pressure (up to $1.4 \cdot 10^5$ Pa) is applied to strain the membrane and the adhered SWNTs. For a given membrane with 108 μm diameter a pressure difference of 10^5 Pa results in straining the SWNT to 0.05%. The corresponding increase in resistance revealed a gauge factor of 300 [22]. Thus, the first pressure sensor transfer function of a SWNT pressure sensor has been demonstrated.

5. CONCLUSIONS

The feasibility of CNT based nano electro mechanical systems (NEMS) is confirmed by the research results of several groups. The direct integration of CNTs into devices will result in the next generation of nanotransducers for mechanical loads. To develop these NEMS it is mandatory to continue research on the control and the reproducibility of the assembly, or even better the growth of CNTs [32], [33]. Self assembly or self assembled growth of nanostructures instead of structuring by photolithographic means will be the preferred process technology approach for nano device integration. Continuous basic research is also needed to integrate CNTs into MEMS on wafer level and to provide fast and efficient methods for CNT pre-evaluation and CNT growth process control.



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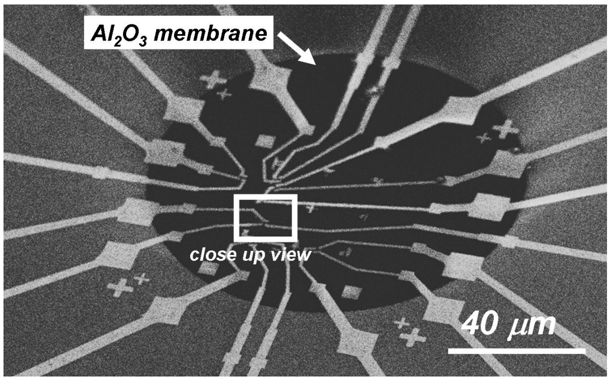

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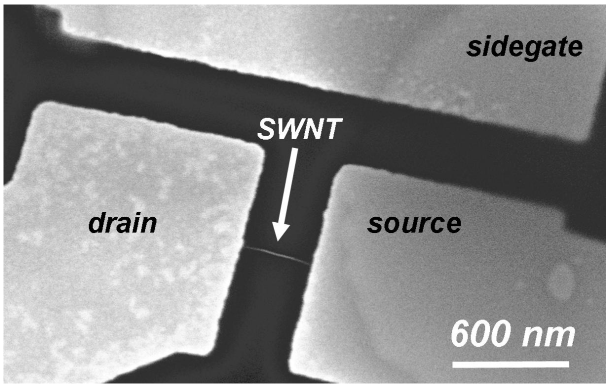

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Figure 2: Membrane based carbon nanotube electro mechanical transducer, i.e. CNT pressure sensor.

a) Concept of a functional building block

b) Bulk micromachined 100 nm thick alumina membrane (diameter 108 μm) with multiple electrode configurations (30 nm Ti/Au electrodes) and several SWNTs adhered to the membrane surface by van der Waals Forces, which are electrically connected to and clamped by the Ti/Au electrodes.

c) Close up view of Fig. 2.b: SWNT on Al_2O_3 membrane with contacts and sidegate.

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REFERENCES

[1] E. Klipp, R. Herwig, A. Kowald, C. Wierling, and H. Lehrach, Systems Biology in Practice: Concepts, Implementation and Application, Wiley-VCH:Berlin 2005.

[2] T. S. Kim, B. Kim, D. d. cho, S. Y. song, P. Dario and M. Sitti, "Fusion of biomedical microcapsule endoscope and microsystem technology," in the Proceedings of the 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea June 5-9, 2005, pp. 9-14.

[3] M. G. Allen, "Micromachined endovasculary-implantable wireless aneurysm pressure sensors: from concept to clinic," in Proceedings of the 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005, pp. 275-278.

[4] P. Cong, K. Olszens, D. J. Young and W. H. Ko, "Implantable blood pressure monitoring of small animal for advanced biological research", in the Proceedings of the 13th International Conference on Solid-State Sensors, Actuators, and Microsystems, Seoul, Korea, June 5-9, 2005, pp. 2002-2005.

[5] C. Hierold, "From micro to nano systems: mechanical sensors go nano", J. Micromech. Microeng., 14, pp. 1-11, September 2004.

[6] S. Iijima, "Helical M. of graphitic Carbon", Nature, vol. 354, pp. 56-58, 1991.

[7] M. S. Dresselhaus, G. Dresselhaus, P. Avouris, Eds., "Carbon Nanotubes: Synthesis, Structure, Properties and Applications", Vol. 80, Springer, Berlin, 2001.

[8] R. Saito, G. Dresselhaus, M.S. Dresselhaus, "Physical Properties of Carbon Nanotubes", Imperial College Press, 2001.

[9] S. Reich, C. Thomsen, J. Maultzsche, "Carbon Nanotubes", Wiley-VCH, 2003.

[10] B. Bhushan, "Handbook of Nanotechnology", Springer, pp. 66, 2004.

[11] P. Zhang, Y. Huang, P. H. Geubelle, P. A. Klein, K. C. Hwang, "The elastic modulus of single-wall carbon nanotubes: a continuum analysis incorporating interatomic potentials," International Journal of Solids and Structures, vol. 39, pp. 3893-3906, 2002.

[12] P. A. Williams, S. J. Papadakis, A. M. Patel, M. R. Falvo, S. Washburn, and R. Superfine, "Fabrication of nanometer-scale mechanical devices incorporating individual multiwalled carbon nanotubes as torsional springs", Appl. Phys. Lett., vol. 82, pp. 805-807, 2003.

[13] H. Miyashita, T. Ono, and M. Esashi, "Nanomechanical structures with integrated carbon nanotube" in Proc. Transducers'03, 2A1.2, pp. 182-185, 2003.

[14] A. M. Fennimore, T. D. Yuzvinsky, W.-Q. Han, M. S. Fuhrer, J. Cumings, and A. Zettl, "Rotational actuators based on carbon nanotubes", Nature, vol. 424, pp. 408-410, 2003.

[15] T. Rueckes, K. Kim, E. Joselevich, G. Y. Tseng, C.-L. Cheung, and C. M. Lieber, "Carbon nanotube-based nonvolative random access memory for molecular computing," Science, vol. 289, pp. 94-97, 2000.

[16] S. W. Lee, D. S. Lee, R. E. Morjan, S. H. Jhang, M. Sveningsson, O. A. Nerushev, Y. W. Park, and E. E. B. Campbell, "A three-terminal carbon nanorelay," Nanoletters, vol. 4, no. 10, pp. 2027–2030, 2004.

[17] S. J. Papadakis, A. R. Hall, P. A. Williams, L. Vicci, M. R. Falvo, R. Superfine, and S. Washburn, "Resonant oscillators with carbon-nanotube torsion springs," Phys. Rev. Lett., vol. 93, no. 14, pp. 146101(1-4), 2004.

[18] M. Nishio, S. Sawaya, S. Akita, and Y. Nakayama, "Carbon nanotube oscillators towards zeptogram detection," Appl. Phys. Lett, vol. 86, pp. 133111(1-3), 2005.

[19] S.N. Cha, J.E. Jang, Y. Choi, G.A.J. Amaratunga et al., „Fabrication of a nanoelectromechanical switch using a suspended carbon nanotube", Appl. Phys. Lett., 86, 083105, 2005

[20] C.K.M. Fung, M.Q.H. Zhang, R.H.M. Chan and W.J. Li, "A PMMA-Based Micro Pressure Sensor Chip using Carbon Nanotubes as Sensing Elements", in Proc. MEMS 2005, pp. 251-254.

[21] C.K.M. Fung, M.Q.H. Zhang, Z. Dong and W.J. Li, "Fabrication of SWNT-Based MEMS Piezoresistive Pressure Sensors Using DEP Nanoassembly," in the Proceedings of the 5th IEEE Conference on Nanotechnology, Nagoya, Japan, July 2005.

[22] C. Stampfer, T. Helbling, D. Obergfell, B. Schöberle, M. K. Tripp, A. Jungen, S. Roth, V. M. Bright, C. Hierold, "Fabrication of single walled carbon nanotube based pressure sensors", in preparation

[23] P. Dharap, Z. Li, S. Nagarajaiah, and E. V. Barrera, "Nanotube film based on single-walled carbon nanotubes for strain sensing," Nanotechnology, vol. 15, pp. 379-382, 2004.

[24] R. J. Grow, Q. Wang, J. Cao, D. Wang and H. Dai, "Piezoresistance of carbon nanotubes on deformable thin-film membranes", Appl. Phys. Lett., vol. 86, pp.93104-93107, 2005.

[25] J. Cao, Q. Want, and H. Dai, "Electromechanical properties of metallic, quasimetallic, and semiconducting carbon nanotubes under stretching", Phys. Rev. Lett., vol. 90, pp. 15760(1-4), 2003.

[26] T.W. Tombler, C.W. Zhou, L. Alexseyev, J. Kong, H.J. Dai, L. Lei, C.S. Jayanthi, M.J. Tang, and S.Y. Wu, "Reversible electromechanical characteristics of carbon nanotubes under local-probe manipulation", Nature, vol. 405, (6788), pp. 769-772, 2000.

[27] A. Maiti, A. Svizhenko, and M.P. Anantram, "Electronic transport through carbon nanotubes: Effects of structural deformation and tube chirality", Phys. Rev. Lett., vol. 88, (12), 2002.

[28] C. Stampfer, A. Jungen and C. Hierold, "Fabrication of Discrete Nano-Scaled Force Sensors Based on Single Walled Carbon Nanotubes," IEEE Sensors Journal, submitted 2005.

[29] C. Stampfer, A. Jungen and C. Hierold, "Single Walled Carbon Nanotubes as Active Elements in Nano Bridge Based NEMS," The 5th IEEE Conference on Nanotechnology, Nagoya, Japan, July 11-15, 2005.

[30] C. Stampfer, A. Jungen and C. Hierold, "Nano Electromechanical Transducers based on Single Walled Carbon Nanotubes," The 13th International Conference on Solid-State Sensors, Actuators Microsystems, Seoul, Korea, June 5-9, 2005, pp. 2103-2106.

[31] T. Helbling, C. Stampfer, B. Schöberle, M. Tripp, A. Jungen, C. Herrmann, S. George, V. Bright, C. Hierold, "Fabrication of Pressure Sensors Based on Ultra Thin Al2O3 Membranes and SWNTs as Active Elements", in Proceedings of the EUROSENSORS XIX (September 11th-14th, 2005), Barcelona, Spain, 2005.

[32] A. Jungen, C. Stampfer, J. Hoetzel, C. Hierold, "Novel Process Flow for the Integration of Carbon Nanotubes into MEMS", in Digest of Technical Papers of the 2005 International Conference on Solid State Sensors, Actuators and Microsystems, Transducers2005, Seoul, pp. 105-108, 2005.

[33] A. Jungen, C. Stampfer, M. Tonteling, S. Schiesser, D. Sarangi, C. Hierold, "Localized and CMOS Compatible Growth of Carbon Nanotubes on a 3 x 3 µm2 Microheater Spot", in Digest of Technical Papers of the 2005 International Conference on Solid State Sensors, Actuators and Microsystems, Transducers2005, Seoul, pp. 93-96, 2005.