NANO ELECTRO MECHANICAL SYSTEMS WITH SINGLE WALLED CARBON NANOTUBES AS FUNCTIONAL ELEMENTS

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Abstract: Sensors are key components in mechatronic systems. Further system miniaturization will demand for continuous down-scaling of sensor functions in such systems most likely towards nano scale. Then new sensor device concepts will emerge to maintain performance, e.g. sensitivity, or to utilize unique functional properties of nano scale structures. This paper presents concepts to create nano electro mechanical sensors based on carbon nanotubes (CNTs). Suspended single walled CNT based cantilever and bridge structures and a membrane based CNT pressure sensor are introduced and discussed. Measurements on the pressure sensor prove metallic single walled CNTs as exceptional piezoresistive electro mechanical transducers with gauge factors above 200.

Keywords: nano electro mechanical systems, NEMS, carbon nanotubes, sensors, pressure sensor

1. INTRODUCTION

Further system miniaturization in mechatronic systems will certainly create demands for a continuous down-scaling of sensor functions in a variety of different application fields (Hierold et.al., 2005). 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 (Klipp et.al., 2005), will starve for sensors to provide data for model verification. Implantable devices like future autonomous micro robots or multifunctional endoscopes (Kim et.al., 2005) for minimal invasive diagnostics (Allen, 2005), health monitoring (Cong et.al., 2005), 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 (Hierold, 2004). 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 (Iijima, 1991) are one of the most intensely studied nanostructures to date (Dresselhaus et.al., 2001; Saito et.al., 2001; Reich et.al., 2003) and are very promising for the further miniaturization of sensors due to their unique properties. Single walled 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 (Bushan, 2004)). Depending on the structural symmetry, which is described by the terms armchair, zig-zag or chiral type tubes, they can exhibit either metallic or semiconducting behavior. Moreover, they are highly elastic with Young's modulus in the range of 1 TPa (Zhang et.al., 2002). 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 (Williams et.al., 2003; Miyashita et.al., 2003; Fennimore et.al., 2003). Some of the many application ideas for utilizing CNTs as structural mechanical elements include data storage (Rueckes et.al., 2000), relays (Lee et.al., 2004), oscillators (Papadakis et.al., 2004; Nishio et.al., 2005), switches (Cha et.al., 2005), and sensors (Fung et.al., 2005a; 2005b; Stampfer et.al., 2006b; Dharap et.al., 2004; Grow et.al., 2005).

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. (2005) 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. (2003) reported effective piezoresistive gauge factors of between 600 and 1000. In the experiment of Tombler et al. (2000), 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 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

In order to evaluate new device concepts based on CNTs, SWNTs have been integrated into MEMS-like structures (Stampfer et.al., 2005a, 2005b, 2006a). Examples are shown in Fig. 1 and Fig. 2.

Fig. 1a shows an illustration of a potential nano scaled accelerometer based on individual SWNTs. The basic functionality of this device is as following: an individual SWNT is connected to and fixed by electrodes and it is suspended from the substrate. If now an external out-of-plane force acts on the freestanding disc (e.g. due to an acceleration *a* of the seismic mass *m*) the support springs deflect, which finally leads to a mechanical deformation (mainly stretching of the nanotube branches) of the clamped SWNT. The support spring (i.e. MEMS like beams, see Figs. 1a, 1b and 1c) provides a precise mechanical interface to the tube, applying local deformation at the edges and axial strain in the branches of the nanotubes. To investigate the proposed transducer concept we studied cantilever and bridge (Figs. 1b and 1c) based structures which have been actuated by an atomic force microscope.

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. AFM measurements are also taken to determine the diameter of the tubes and thus separate the SWNTs from multi-walled CNTs and bundles. Electron beam (e-beam) lithography is subsequently used to pattern (lift-off) the metallic electrodes for the nanoscale structures (see Fig. 1b).

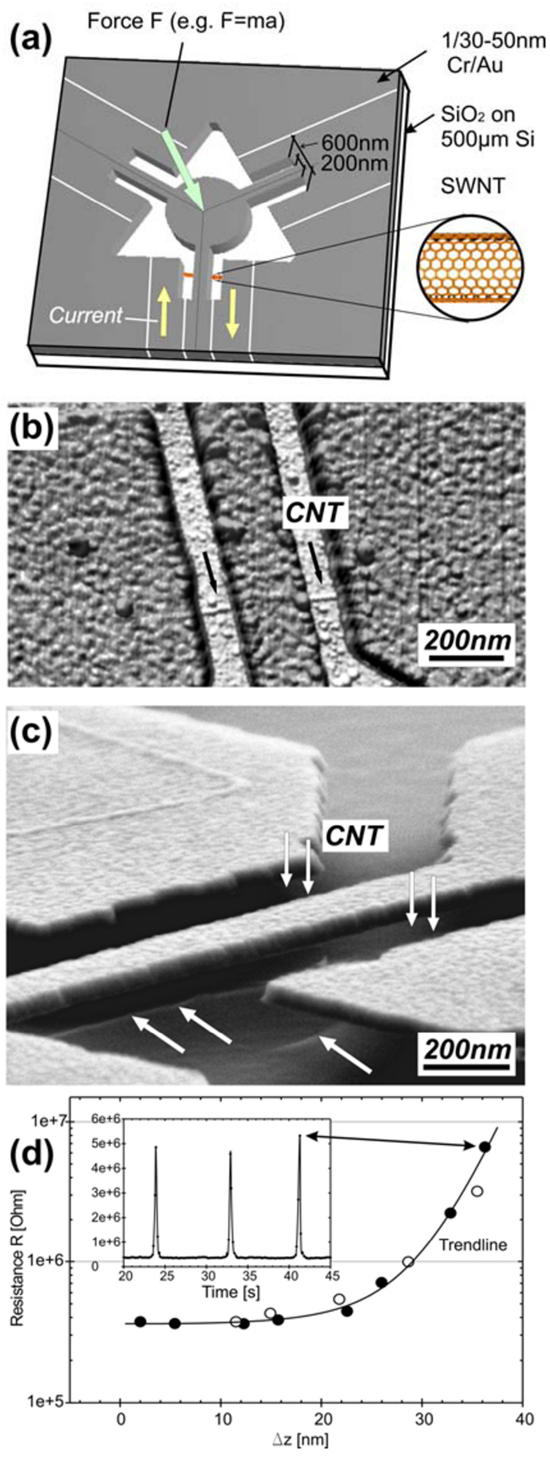

Fig 1. (a) Schematic concept illustration of a single-walled carbon nanotube based nanoscaled sensor system. (b) AFM-image of a fabricated functional building block before the final HF release (cantilever). (c) Finalized device of a bridge based test structure; note the clear undercut of the structure. (d) Electromechanical measurements on a cantilever based structure. The resistance R is plotted on a log scale as a function of the nanotube deflection Δz. ● indicate the measurement points related to pushing down and ○ to the release of the force. Note that (b), (c) and (d) origin from different devices.