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Multi-walled carbon nanotubes integrated in microcantilevers for application of tensile strain

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Abstract

Individual multi-walled carbon nanotubes were positioned on silicon oxide microcantilevers using nanomanipulation tools. A silicon nanowire with a diameter of 200 nm is positioned across the nanotube, and serves as shadow mask during deposition of conducting electrode material, leading to a 200 nm gap in the cantilever electrode only connected by the nanotube. By deflecting the cantilever, tensile strain of the nanotube up to 0.6% can be applied, with negligible transverse deformation or bending. Measurements of the conductance as a function of strain on different samples showed large variations in the response. Using a simple resistor model we estimate the expected conductance-strain response for a multi-walled carbon nanotube, and compare to our results on multi-walled carbon nanotubes as well as measurements by others on single-walled carbon nanotubes. Integration of nanotubes or nanowires with microcantilevers could lead to highly compact force feedback sensors for characterization and manipulation of nanostructures.

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Keywords: Cantilever; Sensor; Nanotube

1. Introduction

The possibility of using structures such as carbon nanotubes and nanowires [1] as readymade mechanical or electrical components in microfabricated devices, has led to the construction of field-effect transistors [2–4] quantum dots [5], gas- and biosensors [6,7], field-emitters [8] and logic circuitry [9]. Recently, the electromechanical properties of carbon nanotubes have attracted much attention. Stretching of a single-walled carbon nanotube (SWCNT) is expected to cause conductance changes through changes in the energy bandgap [10–12]. By pressing the tip of an atomic force

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microscope (AFM) on a suspended SWCNT, Tombler et al. [13] measured an increase in resistance of about two orders of magnitude for a strain ε of 3%, which translates into a gauge factor, $g = \Delta R/\varepsilon R$, of order 10^3. These variations were mainly attributed to transverse deformations induced by the AFM tip such as bending and collapse of the tube.

However, calculations considering both the effect of transverse deformations and stretching on conductance performed by Maiti et al. [14] indicated that the main cause of change in conductance was tensile stretching rather than transverse deformation, and that the conductance response to tensile strain is highly dependent on bandstructure; while armchair nanotubes are hardly affected, zig-zag nanotubes undergo conductance changes comparable to the semiconductor piezoresistors. A second set of experiment by Cao and co-workers [11] using a different geometry with more uniform tensile deformation, showed distinct differences in response that were related to the bandstructure of the nanotubes, and also found that the responses were generally larger than what should be expected from purely stretch-induced changes in bandgap. The authors could not rule out the possibility of transverse deformations, due to the method of stretching.

At this point, no measurements of the strain sensitivity of multi-walled carbon nanotubes (MWCNT) resistance have been performed. MWCNT are much easier to manipulate than SWCNT, and it is also an interesting question in which way the shell structure with several shells contributing with different levels of strain sensitivities, will affect the total response.

In this work we studied the response of MWCNT fixed mechanically and electrically on a microcantilever using a nanowire as a shadow mask in a metallization step, in order to create a narrow gap in the electrode layer on the cantilever, and thereby forming source and drain contacts to the MWCNT. A similar method was used to electrically contact carbon nanotubes by Pablo et al. [15], however, using a 4.3-μm-diameter tungsten wire across a carbon nanotube resting on a planar substrate. Deflecting the cantilever creates a nearly pure tensile strain in the nanotube with negligible transverse deformation. We have investigated a few devices made with this technique and observe large variations in the response, which we compare to a simple model treating the individual shells as resistors in a network. The method opens for the possibility of using a MWCNT or other type of strain-sensitive wire or tube as a strain gauge on a microcantilever, which could lead to very compact force-feedback probes.

2. Experimental setup

Microchips equipped with two or four microcantilevers were fabricated using conventional silicon microfabrication techniques [16,17]. The microcantilevers are 1-μm-thick and 4–8-μm-wide silicon oxide cantilevers, which can be covered with a thin metallic coating that allows the cantilevers to be used for multi-point electrical measurements [16].

The MWCNTs investigated were grown by chemical vapor deposition at Clemson University with diameters up to 100 nm. The silicon nanowires used as shadow masks were single-crystalline, 10–100-μm-long, 200–300-nm-wide wires fabricated by a deep etching technique at Phillips research laboratories [18].

The experimental setup is based on an optical Navitar objective lens, which in combination with a CCD camera allows for viewing MWCNT or bundles of nanotubes with diameters down to 20–30 nm when these are placed on a reflecting surface. A Newport XYZ stage with 50 nm resolution is used for sample positioning, while one or two microcantilever tools are mounted on independent Burleigh PCS-300 piezo-manipulators with 300 μm travel range and roughly 50 nm precision. Conductance measurements were performed using a Keithley 2400 combined current source and voltmeter. Fig. 1a illustrates the procedure for assembly of a MWCNT strain gauge. The procedure includes the following steps: (i) a single MWCNT is isolated from the sample using an etched tungsten tip as manipulation tool. (ii) The nanotube is placed on a 3–8-μm-wide microcantilever. By manipulating the nanotube on the surface of the target cantilever using the