Parallel Fabrication of Single-Walled Carbon Nanotube based Piezoresistive Pressure Sensors

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ABSTRACT

A major obstacle in the realization of commercially viable single-walled carbon nanotube (SWNT) based devices is their type and site selective integration. In this work, dielectrophoresis is used in the purely parallel fabrication of extremely small SWNT-based piezoresistive pressure sensors. Superior strain sensitivity to state-of-the-art silicon based piezoresistive pressure sensors is achieved through the highly selective integration of individual small band gap semiconducting (SGS)-SWNTs and precise carbon nanotube placement on the designated membrane edges, ultimately the positions of highest strain. The SWNTs are encapsulated by a protective alumina coating to ensure long-term stability and avoid environmental influences. The scale-up of the introduced robust and reliable fabrication process is straight-forward and provides promising avenues toward successful realization of functional, commercially viable SWNT sensors.

Keywords: microelectromechanical systems, carbon nanotubes, parallel integration, dielectrophoresis, piezoresistivity

1 INTRODUCTION

Piezoresistivity based pressure sensors consist of two primary components: a membrane and a transducer element. Traditionally, both elements are made up of silicon. State-of-the-art membrane dimensions are 250x250 μm^2 [1]. In an effort to significantly reduce the size of microelectromechanical systems (MEMS) toward realizing nanoelectromechanical systems (NEMS), single-walled carbon nanotubes (SWNTs) are anticipated to take over as transducer element in piezoresistivity based pressure sensors. Straining SWNTs modifies their electronic bandgap and the electrical response can be used to infer the applied pressure on the sensor [2]. Earlier proofs of concepts show high promise for SWNT based strain sensing applications because of enhanced sensitivity (gauge factors up to 500), ultra-small size, and significantly reduced drive current requirements [2-6].

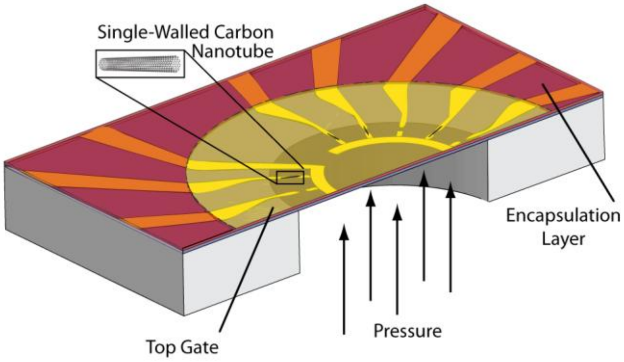

Figure 1: Carbon nanotubes are aligned in radial direction on the edges of the circular membrane of the pressure sensor, the regions of maximum strain. Exclusively parallel integration techniques are used in the sensor fabrication.

Traditional process technologies which integrate individual SWNTs, however, are not suited for large-scale low-cost device fabrication, as each carbon nanotube must be individually located and separately contacted. This serial customized processing creates a major bottleneck in SWNT based device fabrication.

Dielectrophoresis is an electric field based technique which allows the bridging of multiple contacted electrode gaps non-intrusively by micro- and nanoscaled objects on a single device in a parallel fashion [7]. The method permits the selective deposition or directed movement of spherical, one- and two-dimensional objects in non-uniform electric fields.

2 DEVICE FABRICATION

The parallel fabrication of SWNT based piezoresistive pressure sensors consists of two essential elements. First, the carbon nanotubes are dielectrophoretically positioned between predefined electrodes, before the pressure sensor membrane is released by bulk micromachining and final encapsulation and connections are made.

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2.1 Dielectrophoresis

When a non-uniform electric field is applied to dispersed particles, they dielectrophoretically move toward the regions of highest electric field strength if the polarizability of the particles is greater than that of the suspending medium, otherwise they are repelled [7]. The controlled deposition of individually accessible devices at very high integration densities and minimal external contacting is achieved by capacitively coupling the metallic leads to a conductive substrate [8-10]. Additionally, under this scheme direct current throughput through the nanostructures during the assembly process is avoided.

The SWNTs, acting as piezoresistors in the present application, are preferably placed at the location of highest stress/strain, generally the edge of a circular or rectangular membrane (Figure 1). Prefabricated electrodes were prepared by photolithography, metal evaporation and lift-off on a 70 nm thick thermal dry oxide grown on doped silicon. A droplet of individually dispersed aqueous SWNT solution was then dispensed on the chip for dielectrophoretic nanotube assembly, and a sinusoidal potential of 0.5 V_p at 100 MHz applied to the contacted bias electrode and grounded substrate by a high frequency, high power signal generator for 60 s [11].

Characterization of the deposited SWNTs was carried out by scanning electron microscopy (SEM), atomic force microscopy (AFM) and electrical transport measurements. After integration, on the average 20-30% of the separately accessible electrode gaps were bridged by an individual carbon nanotube. The deposited SWNTs were in general straight, thus minimizing non-principal strain components and local bandgap opening by bending (Figure 2). A 90% electrical characterization yield was achieved on all probed SWNTs. Since only one functional carbon nanotube is required on the finalized pressure sensor, this integration yield is more than sufficient.

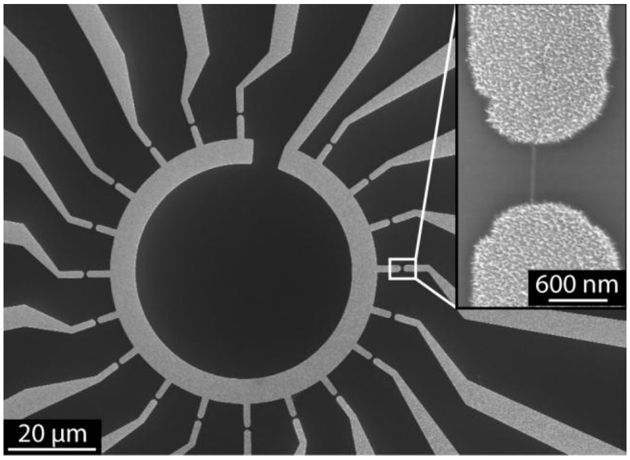

Figure 2: The SWNTs are dielectrophoretically and individually assembled in a parallel manner on prefabricated circularly arranged electrodes. (Scanning electron microscope image)

2.2 Micromachining

To improve SWNT contact adhesion, rapid thermal annealing at 400°C for 1 min was performed in a nitrogen environment. Then high *k* alumina dielectric was used from an atomic layer deposition (ALD) process to encapsulate the carbon nanotubes. Encapsulation not only provides protection against environmental influences but also ensures long-term stability [12]. In a final deposition process a metallic top gate was evaporated for carbon nanotube field effect transistor (CNFET) gate modulation.

The last fabrication step consisted of backside alignment to structure the membrane and its release by dry etching. The tri-layer silica/alumina/gold membrane is 190 nm thick and 100 µm wide in diameter (Figure 3). For electromechanical characterization the chips were packaged to into a ceramic chip carrier in a dedicated pressure chamber and the electrodes wire-bonded.

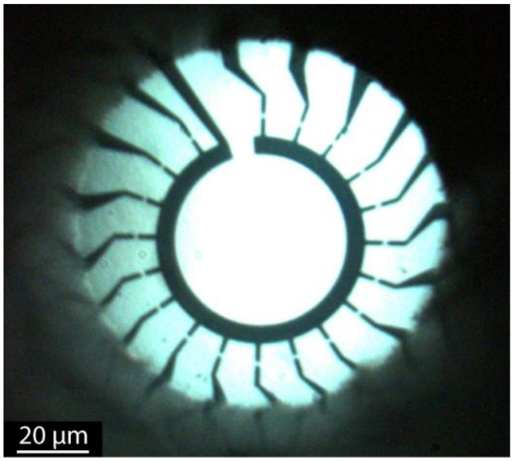

Figure 3: After the 100 µm diameter membrane release, the integrated SWNTs are located in radial direction towards the edges of the membrane, the regions of maximum stress/strain when subject to a uniform load. (Optical microscope image)

3 SENSOR PERFORMANCE

Figure 4 shows time dependent measurements of a completed pressure sensor. A source-drain potential of V_{sd}=50 mV was applied to the SWNT transducer element and the resulting current recorded. The upper curve in the graph displays the output current I_{sd} against an applied pressure p in the lower curve. Quick ramp rates caused an overshoot of the pressure in the chamber, which was able to be detected by the fast current responses of the carbon nanotubes. A sensor sensitivity of S_0=0.25 $\Delta R\ R^{-1}\ bar^{-1}$ was extracted from the measurements with a resolution better than 50 mbar at a power consumption of less than 40 nW. The presented SWNT exhibits negative piezoresistive behavior, decreasing its resistance with increasing strain.

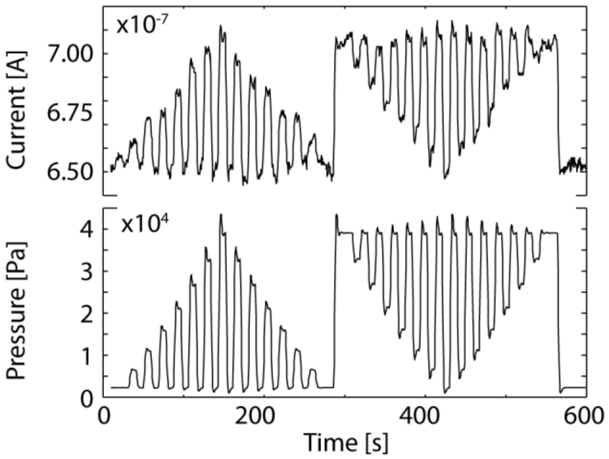

Figure 4: The SWNT transducer elements evidence very quick response and high sensitivity to applied pressures during quasi-static measurements.

The SWNT transducer elements always evidenced CNFET behavior with varying on-off ratios. The electrical responses were classified into two categories, small and large on-off ratios. For categorization purposes a cut-off value of 3 was introduced, while small bandgap semiconducting (SGS-)SWNTs generally displayed on-off ratios of less than 2 and large bandgap semiconducting (s-)SWNTs a ratio higher than 10 [11]. Zig-zag and chiral metallic SWNTs exhibit a small bandgap in the range of $k_B T$=26 meV from curvature effects due to the cylindrical structure of the hexagonal carbon structure [13]. No perfectly metallic SWNTs, without any dependence on the gate voltage, were found in the study, most probably due to non-perfect experimental SWNT alignment.

Previous studies have shown that the signal-to-noise ratio of SWNT-based piezoresistive pressure sensors is highest in the off-state of SGS-SWNTs because the off-state currents remain high due to the small bandgap in SGS-SWNTs and the amplitude of the low frequency noise corrupting the signal remains low [14-15]. For a high integration yield of highly sensitive devices the selective integration of SGS-SWNTs must therefore be possible. This feat can be achieved by the selective metallic dielectrophoretic integration at high deposition frequencies since SGS-SWNTs exhibit metallic permittivity behavior due to their small bandgap [16-17].

The model of thermally activated transport, which describes the carbon nanotube bandgap opening imposed by strain, specifies that the SWNT gauge factor is not only dependent on SWNT chirality, but also on contact properties and device transmission [2]. Ohmic contacts and low device resistance are therefore an essential element to enhance sensor sensitivity. Palladium (Pd) and large-diameter carbon nanotubes combine for low-resistance contacts, due to a high metal work function, good wetting interaction and reduced contact barrier heights from smaller carbon nanotube bandgaps [18-19].

The long-term operation of the sensors over a period of three months was confirmed in the measurements. The protective dielectric encapsulation guarantees this long-term stability.

Sensor sensitivity in a specific and well defined application range may be improved by optimizing the membrane thickness and stiffness, as well as minimizing initial stress. With a precise finite element model (FEM) evaluating the tri-layer membrane thickness and diameter influence on the induced strain, a membrane characterization from a bulge test can be used for a detailed gauge factor analysis of the piezoresistive carbon nanotube transducer properties [15].

4 CONCLUSIONS

The reported measurement observations are consistent with previous reports using serial fabrication methods [14-15]. The sensitivity and resolution of the pressure sensors are highest in the off-state of SGS-SWNTs. Also device resistance properties are observed to have a major influence on the electrical response of the pressure sensors. Growth induced SWNT diameter variation and non-equal electrode coverage are thought of being the primary reasons for device performance differences.

To achieve even higher carbon nanotube gauge factors, contact resistance has to be minimized and carbon nanotube transmission increased. Top side metallization offers one potential approach.

An additional benefit of the introduced fabrication method is that multiple carbon nanotubes can be assembled onto one membrane and that the best performing specimens can then be selectively integrated together in a Wheatstone bridge configuration to cancel out temperature cross-sensitivity. Consequently, a comparatively low integration yield is sufficient without causing any substantial increase in fabrication costs due to the exclusive use of parallel assembly techniques.

All the above elements demonstrate the robustness of the parallel small membrane pressure sensor fabrication process and reliability of the SWNT transducer elements. Because of the purely parallel processes involved, especially for the individual SGS carbon nanotube integration, it is expected that large-scale fabrication is straight forward and entails substantial cost benefits. Overall, a high industrial and commercial potential is perceived.

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