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Extended width in discontinuously connected polymer-free carbon nanotubes grown between electrodes

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ABSTRACT

Polymer-free carbon nanotubes (CNTs) grown between single-gap (SG) and interdigital-gap (IG) electrodes were used to develop miniature strain gauges. The strain and stress of the gauges were approximated according to the distance lift of a screw on a cantilever silicon substrate. In our preliminary study, electrical characterization indicated the gauge factors (GFs) of SG and IG devices to be approximately 36 and 1500, respectively. This result suggests that an extended width in IG electrodes, generating a larger amount of CNTs, provides a smaller minimum tunneling distance than does the width in SG electrodes. The distance shift under a small distance is expected to generate a high ratio of tunneling resistance change. The sparser and denser distributions of CNTs in SG and IG electrodes probably caused the gauges to exhibit capacitive and inductive features, respectively. Despite having substantial GFs, the gauge may require improvement in packaging to resist environmental effects and the growth of homogeneous CNTs and, thus, be reproducible.

1. Introduction

Smaller mechanical and electrical devices with high-resolution and small-scale sensors are currently preferred. Carbon nanomaterials, such as carbon nanotubes (CNTs) or graphene, demonstrate excellent electrical and mechanical properties for use in miniature devices. Dispersing carbon nanomaterial films and fillers in an insulating polymer is a potential approach for developing miniature strain gauges [1–18]. In general, carbon nanomaterial films dispersed in a polymer exhibit a lower gauge factor (GF) than do carbon nanomaterial fillers dispersed in a polymer because the GF mechanism underlying the changes in the conduction of films and fillers is different. The GF mechanism for fillers dispersed in a polymer depends on the changes in tunneling resistance, and that for carbon nanomaterial films depends on deformation. Nanoconductive wires, including CNTs, that have a high aspect ratio can be used as polymer fillers to provide effective tunneling pathways under strain. Previous studies have indicated that the conductive network and tunneling effects contribute to the GF more than they contribute to CNT piezoresistivity and contact resistance in CNT/polymers in strain gauges [1–3]. The tunneling effect and conductive network in CNT/polymer strain gauges are determined by several factors, including the concentration, orientation, and conductivity of CNTs or nanoconductive wires as well as the polymer type [4–10]. The theory of electrical percolation threshold indicates that the GF increases approximately 100-fold when a CNT/polymer is switched from the overlapping contact to the tunneling resistance mode [11]. Tunneling conductivity exponentially increases with the tunneling distance [10,12]. Currently, the maximum GF reported for a gauge consisting of a CNT/polymer is approximately 100 [4], and the tunneling effect is introduced when the distance between two CNTs is <1 nm in a resistor network based on a numerical model [1]. The critical path theory states that the maximum conductivity determines the overall conductivity in a resistor network [19,20]. The dominant resistance in CNT/polymer strain gauges may thus be simplified as a critical path for electric current [Fig. 1(a)]. The overall resistance change depends on the minimum resistance ($_{min}$) path (i.e., the critical path). The GF of a strain gauge enhanced through tunneling may largely rely on this path. However, a polymer-embedded conductive path can be rigid, possibly limiting the tunneling distance change and, thus, the GF. The absence of a polymer probably enables the CNTs to move freely as the external force is enforced, enhancing the changes in tunneling current compared with those in CNT/polymer gauges. In addition, polymers have relatively low dielectric constants; however, their values are higher than the value of air, enabling the tunneling current in air to easily hop from one CNT to another. Tunneling resistance ratio after strain (r_1) and before strain (r_0) for two individual CNTs exponentially varies with tunneling distance of nearby CNTs [8], as follows:

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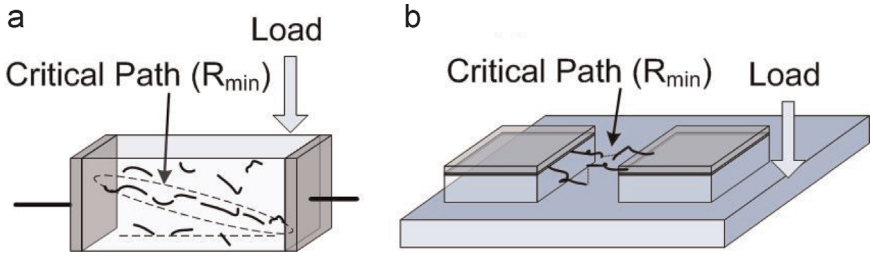

Fig. 1. Schematic of (a) a typical CNT/polymer strain gauge and (b) a polymer-free CNT strain gauge showing the changes in the tunneling resistance of their critical paths.

$$\frac{r_1}{r_0} = \frac{s_1}{s_0}\frac{A_0}{A_1}\exp\left[\frac{4\pi\sqrt{2m\varphi}}{h}(s_1 - s_0)\right], \quad (1)$$

where s_1 and s_0 are the distances, A_1 and A_0 are conduction areas between CNTs, m is the electron mass, φ is the barrier height of CNT, h is Planck's constant, and ψ is the function related to the orientation angle and Poisson's ratio. The equation implies that a slight shift between the two CNTs can substantially affect the tunneling resistance change. Therefore, this study proposes using polymer-free CNTs instead of a CNT/polymer as tunneling pathways [Fig. 1(b)]. The figure shows that in situ CNT growth provides a stronger electrical connection between two electrodes compared with that in CNT/polymer gauges because the CNTs are grown directly between the electrodes by using a nickel (Ni) catalyst located underneath. The electrodes in a single-gap (SG) device were designed to increase the width and, thus, produce a greater number of CNTs in an interdigital-gap (IG)-electrode device.

2. Experiments

2.1. Interdigital-gap and single-gap patterns and growth of carbon nanotubes on interdigital-gap and single-gap patterns

Silicon dioxide (500 nm thick) and Ni films (5 nm thick) were deposited on a silicon wafer as an insulator and a catalyst for CNT growth, respectively. The wafer was then pretreated with hydrogen at a flow rate of 1000 sccm. A 300-nm-thick titanium film was deposited to create contact electrodes. Two patterns were developed through subsequent photolithography and etching. Fig. 2 (a) and (b) shows micrographs of CNT growth over electrodes of SG and IG devices and the formation of a contact between these electrodes, respectively. Horizontal hot-wall atmospheric chemical vapor deposition was used to facilitate CNT growth. The chamber was initially preheated to 800 °C and pretreated with hydrogen (H_2) and ammonia (NH_3) at respective flow rates of 1000 and 100 sccm for 15 min. The CNTs were then grown using precursor methane (CH_4) as the carbon source at a flow rate of 400 sccm; H_2 and NH_3 were added at respective flow rates of 200 and 50 sccm for 30 min. SG-1 [Fig. 2(c)] grown on the same chip exhibited sparser growth than did IG-1 [Fig. 2(d)]. The insets in Fig. 2(c) and (d) show that the CNTs grew only on the surrounding side walls because of their exposure to the Ni catalyst. The diameter of the CNTs ranged from 60 nm to 70 nm. The gap between the SG and IG electrodes was set to 2 μm; however, the gaps were slightly widened after the process, as observed in the micrographs. In this study, the polymer-free CNTs were connected to the electrodes in parallel [Fig. 1(a)], whereas the CNTs were connected to the electrodes in series in CNT/polymer gauges [Fig. 1(b)]. Therefore, the extended width in the IG electrode caused the electrode to exhibit a considerably lower overall resistance than that of the SG

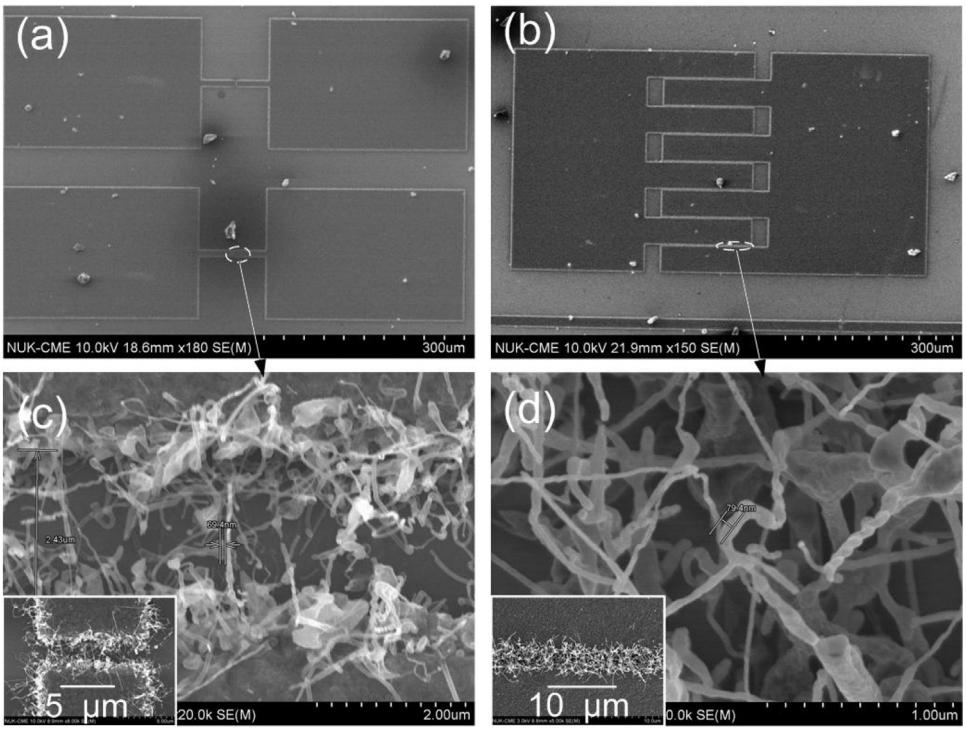

Fig. 2. Micrographs of (a) SG and (b) IG electrode patterns with CNTs around their sides and the discontinuous connection between electrodes above the gap, and magnified view of CNT growth in (c) SG-1 and (d) IG-1, which show sparser and denser growth (insets), respectively.