Sensors and Actuators A 180 (2012) 120–126

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A prototype high sensitivity load cell using single walled carbon nanotube strain gauges

Dongil Lee[a], Hyun Pyo Hong[b], Myung Jin Lee[b], Chan Won Park[c], Nam Ki Min[a,b,*]

[a] Department of Biomicrosystem Technology, Korea University, Anam-dong Seongbuk-Gu, Seoul 136-701, Republic of Korea
[b] Department of Control and Instrumentation Engineering, 208, Seochang-ri, Jochiwon, Yeongi, Chungnam 339-700, Republic of Korea
[c] Department of Electrical and Electronics Engineering, Kangwon National University, Chuncheon, Kangwon 200-701, Republic of Korea

ARTICLE INFO

Article history:
Received 27 October 2011
Received in revised form 8 April 2012
Accepted 14 April 2012
Available online 22 April 2012

Keywords:
Strain sensor
Microfabrication
SWCNT
Load cell
Force sensors

ABSTRACT

This paper presents a novel strain gauge made of single walled carbon nanotube (SWCNT) film and further discusses the usability of load cells with these gauges as sensors for force and weighing measurements. Key issues involve the deposition of the SWCNT films with strong adhesion to the backing materials, the integration of SWCNT films into existing micro technologies for batch-fabrication, and the bonding of the strain sensors to a binocular spring element. The batch-fabricated SWCNT strain gauges showed the linear relationship between resistance changes and externally applied strain. The sensitivity of the SWCNT gauges was measured to be approximately 30 times higher than that of commercial foil-type gauges. The effectiveness of a microfabricated SWCNT gauge as a force sensor was evaluated by applying it to high sensitivity binocular load cells. Our test results exhibited that SWCNT gauge load cells had much better resolution and higher sensitivity than the conventional metal foil-type cells.

1. Introduction

Strain gauge based sensors have been an important engineering tool since shortly after the invention of the strain gauge in the late 1930s. In addition to their industrial and engineering uses, these sensors are now widely used in many business and consumer products with ever increasing frequency. As a result, there is currently a great deal of interest in strain gauge sensor technology. A load cell is a transducer that converts the force acting on it into a measurable electrical signal when the strain gauges, which are bonded on a spring element or beam, physically deform. Load cells are classified according to the output signal they generate and the way they detect weight: metal strain gauge cells [1–3], mechanical cells [4], fiber optic cells [5], and semiconductor cells [6]. However, most of the today's load cells use metal foil strain gauges as the sensing element because of their high accuracy and low cost. Although the foil-type gauges can serve as low-cost and accurate strain sensors, they have performance limitations such as low resistance, low gauge factors, and temperature-dependent drift. Especially, the gauge factor, dimensions, and resistance are critical to achieve high resolution and low power dissipation.

Due to low gauge factors and low resistances of foil-type gauges, they are not suited for miniature, high-resolution load cells. In the case of load cell designs that have inherently small areas of uniform strain, e.g., the binocular design, a thin spring element is required to realize high sensitivity when using metal foil-type gauges as strain sensors. Such a design will make the sensors more vulnerable to external shocks or vibrations. Moreover, an accurate read out load cell requires sophisticated electronic processing circuitry for transduction.

Gauge dimension is often a very important factor in determining gauge performance under a given set of circumstances. Strain measurements are usually made at the most highly stressed points on a bending beam structure. Associated with stress concentrations, these critical points have a very steep strain gradient, and the area of maximum strain is restricted to a very small region. The strain gauge tends to average the strain over the area covered by the sensing line. Since the average of any nonuniform strain distribution is always less than the maximum strain, a strain gauge which is noticeably larger than the maximum strain region will indicate a strain magnitude that is too low. Strain gauge resistance is another important element in load cell design, primarily, because of its effects on both the output-signal amplitude and power dissipation. The signal–noise (S/N) ratio of the system can be significantly improved by simply increasing the excitation voltage. However, the power dissipated in a gauge rises as the square of the excitation voltage. This rise in power dissipation may cause problems in battery-operated load cells. Moreover, the power dissipation and

* Corresponding author at: Department of Biomicrosystem Technology, Korea University, Anam-dong Seongbuk-Gu, Seoul 136-701, Republic of Korea.
Tel.: +82 2 925 2296; fax: +82 2 3290 3991.
E-mail address: nkmin@korea.ac.kr (N.K. Min).

0924-4247/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2012.04.015

its thermal effects may also cause problems in load cell stability and accuracy. In general, the maximum allowable power dissipation is normally limited by accuracy requirements. In practice, an attractive alternative for increasing the output signal without increasing power dissipation is to use a higher resistance gauge at an increased excitation voltage. The higher resistance gauge is preferable in that it reduces the heat generation rate by a factor of three for the same applied voltage across the gauge. Higher gauge resistance also has the advantage of decreasing lead wire effects such as circuit desensitization due to lead wire resistance, and reducing unwanted signal variations due to lead wire resistance changes with temperature fluctuations. Similarly, when the gauge circuit includes switches, sliprings, or other sources of random resistance change, a higher resistance gauge improves the S/N ratio, operating at the same power level. With these considerations, it is usually advantageous to select the highest practical gauge resistance. However, the resistance of most metal foil-type gauges is only several 100 Ω. Even micro-measurements require strain gauges with resistance up to 5 kΩ in a sensing line size of 1.3 mm × 1.5 mm. To realize high resistance metal strain gauges, the sensing line length has to become much longer and gauge area much larger than the maximum strain region.

To overcome these limitations of metal foil-type gauges, carbon nanotubes (CNTs) have been explored as a novel material to make strain sensors. CNTs are an attractive alternative material for developing new sensors because of their superior electromechanical properties [7–15]. Currently, CNT-based strain sensors are made of individual CNTs, CNT/polymer composites, or CNT films (buckypapers). Both individual single-walled CNTs (SWCNTs) and multi-walled CNTs (MWCNTs) have been found to have excellent piezoresistive properties, which suggest the use of CNTs as strain sensors [8,14]. Gauge factors up to 1000 have been reported for SWCNTs [8], which is significant when compared to that of a metal strain gauge having a gauge factor of about two. Although individual CNTs exhibit excellent strain sensing properties, they have some practical difficulties, such as the complicated fabrication process associated with their integration into micro/macroscopic sensors. Recently, CNT/polymer composite-based strain gauges have been reported in the literature, including SWCNT/polyelectrolyte [16], CNT/polymethyl methacrylate using SWNTs and MWNTs [17,18], MWCNT/polyisoprene [19], MWCNT/epoxy [20], MWCNT/polysulfone [21], MWCNT/polyethylene oxide [22], MWCNT/poly (L-lactide) [23], and MWCNT/polycarbonate [24] strain sensors. These strain sensors have higher gauge factors than conventional foil-type gauges. The major drawback of CNT/polymer composite sensors is that strain sensitivity is strongly dependent on the aspect ratio, content, and dispersion state of the CNTs, as well as the properties of the host polymer. Strain sensing with a pure CNT film (buckypapers) [12,25–29] or CNT yarn sensors [30] has been reported. The CNT film sensors showed higher strain sensitivity than composite sensors, but in tension, they showed nonlinear behavior due to slippage among the CNTs.

While the aforementioned researchers investigated mainly the gauge factor and the stability of the proposed CNT-based strain gauges, a few have developed a device that can easily mount gauges on structural surfaces. Furthermore, their fabrication processes are extremely complicated or time consuming, and thus are not suitable for mass production of practical CNT-based strain gauges.

In this paper, we present the design and prototype testing of a SWCNT film gauge load cell of very high sensitivity and resolution without high gain electronics. SWCNT film strain gauges were fully batch-fabricated using a microfabrication process. Unlike the buckypaper employed by many researchers [17,24,26], the SWCNT thin films used in our study were spray-deposited on a flexible polyimide base, widely used in commercial metal foil gauges, and conventional photolithography was used to pattern the gauges, followed by SWCNT etching in an oxygen plasma. Design parameters such as strain-sensitive CNT line and film thickness were experimentally varied to quantify the changes in the performance characteristics of the spray-coated SWCNT strain gauges. A prototype SWCNT gauge binocular load cell was designed, fabricated and then tested to measure its linearity, gain factor, and resolution characteristics. The experimental results showed that the SWCNT gauge load cells had a much higher sensitivity and higher resolution than the commercial metal foil-type cells.

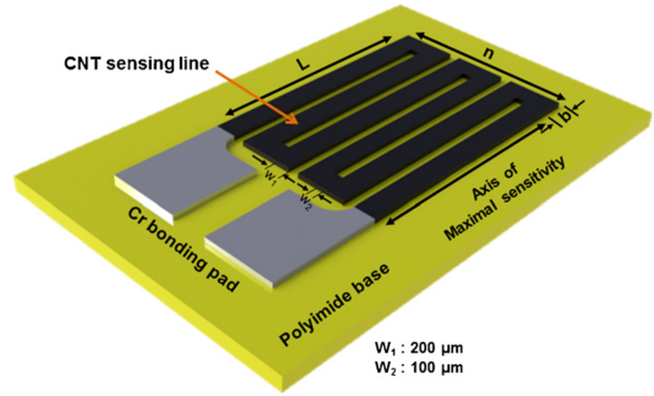

Fig. 1. Layout of the CNT strain gauge design.

2. Design and fabrication of SWCNT film strain gauges

Fig. 1 shows a simplified drawing of a CNT strain gauge design that consists of several strain-sensitive CNT lines bonded to a polyimide base. CNT sensing lines in the direction of the expected strain were made long and thin to maximize the sensitivity of the gauge. End loop responds to strains which are perpendicular to the primary sensing axis of the gauge. Therefore, the end loop was made short and wide to reduce the gauge's transverse response. The solder tabs were considered to be insensitive to strain because of their relatively large cross-sectional area and low electrical resistance. We used a CNT sensing line that was 200 μm wide (w_1) and 3 mm long (L). The distance between sensing lines was 100 μm (w_2). The nominal end loop was 300 μm wide (b) and 500 μm long. The insulation backing (polyimide film) was nominally 5 mm long and 3 mm wide. The nominal thickness of the backing was 15 μm. In our initial study, we intended to make several prototype SWCNT strain gauges to characterize gauge performance as a function of parameter variations in design and fabrication processes. The number of sensing lines, n, was 4, 6, and 8. The SWCNT thickness t was 70 nm, 225 nm, and 280 nm.

The SWCNT film gauges were fully batch-fabricated using a microfabrication process. The major steps are illustrated in Fig. 2 and described as follows. Glass wafers were used as the substrate. Polyimide film was spin-coated over the glass wafer and cured for 1 h at 350 °C in a furnace (Fig. 2a). A 3000 Å Cr film was evaporated onto the polyimide (PI) film. Photolithography was used to pattern the electrode, followed by a wet-etching process with the Cr7 etchant for 60 s (Fig. 2b). To prepare the solutions for the spray-coated films, we used commercially available purified arc-discharge SWCNTs with purity of more than 70% after acid purification (Hanwha Nanotech Co., Korea). SWCNTs were treated by RF oxygen plasma for 20 s at 15 W to enhance SWCNT–polyimide interaction and adhesion. 3 mg of SWCNTs diluted with 150 ml of dichlorobenzene was tip-sonicated for 20 min. The isolated and dispersed SWCNTs were then separated from the aggregated SWCNTs and the insoluble material by ultracentrifugation (20,000 × g, 20 min, 4 °C). The SWCNT film was spray-coated over the PI film