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Fabrication of highly sensitive field emission based pressure sensor, using CNTs grown on micro-machined substrate

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ABSTRACT

Carbon nanotubes have been used as cold cathode emitter in the fabrication of a sensitive field emission pressure sensor. Vertically aligned carbon nanotubes were grown using the plasma-enhanced chemical vapor deposition (PECVD) on a micro-machined silicon substrate. A silicon membrane was used as the flexible anode against the fabricated CNT-based cathode. A 2-μm thick SiO_2 layer has been applied as the anode–cathode spacer and the output results have been compared with a similar sensor with 120 μm spacer. Results show that the sensitivity and the output emission current of the fabricated sensor have been highly improved by decreasing the anode–cathode spacing. Measurements show an ultra-high sensitivity of about 100–970 μA/kPa which is higher than the similar pressure sensors. Low working voltage and high thermal stability of the fabricated sensor are among the other advantages of the presented sensor.

1. Introduction

Electron field emission has recently been used in many applications such as displays, scanning electron microscopy and sensors. Among various emitters, carbon nanotubes (CNTs) have been shown to possess exceptional characteristics for field emission purposes, such as high aspect ratio and high electrical conductivity [1–5]. CNTs also need lower threshold electric fields compared to other materials and have a much higher field emission current making them excellent electron emitters [6–9]. Vertical growth of the nanotubes is a critical factor for their proper electron emission. Among the different methods used for the growth of nanotubes, plasma-enhanced chemical vapor deposition (PECVD) method is frequently used for the vertical growth of carbon nanotubes [10,11].

There are various types of pressure sensors such as peizoresistive, capacitive, and field emission sensors. Operation of these sensors, in general, is based on the deflection of a flexible membrane in response to an external pressure [12]. Micromachined pressure sensors, because of their small dimensions, low cost fabrication, and high performance are attractive to a wide range of applications, such as automotive circuitry, industrial equipment, and laboratory and medical instruments.

The field emission pressure sensors have significant advantages over their counterparts, such as capacitive and piezoresistive sensors. In field emission pressure sensors, the membrane basically acts as the anode against a cold-cathode emitter electrode [13–16]. Applying a pressure difference causes the membrane to deflect which in turn changes the cathode-to-anode distance and thus the electric field at the CNT tips. As a result of the changes in the field, the emission current would vary which could be quite significant, depending on the initial spacing between anode and cathode electrodes. Field emission is very sensitive to electric field, and the cathode temperature has a negligible effect on this property. Therefore, the field emission pressure sensor has the advantages of high sensitivity, temperature stability in addition to resistance against radiation and quick response. On the other hand, the output sensitivity, in piezoresistive and capacitive pressure sensors, is mainly determined by the membrane thickness. This makes a high yield manufacturing process a challenging issue to achieve very thin membrane with well controlled thickness. This is a major obstacle in fabricating piezoresistive and capacitive pressure sensors with high sensitivities [17]. In this paper by taking advantage of the anode/cathode proximity, we will show that high sensitivity can be achieved in field emission pressure sensors. Besides, the electronic circuitry needed for such sensors is much simpler than that used for their counterparts [18–23].

In this experimental study, vertically grown CNTs on micro-machined silicon substrates have been utilized to realize a novel field emission pressure sensor. Then the effect of anode/cathode spacing on the sensor output behavior has been investigated. The

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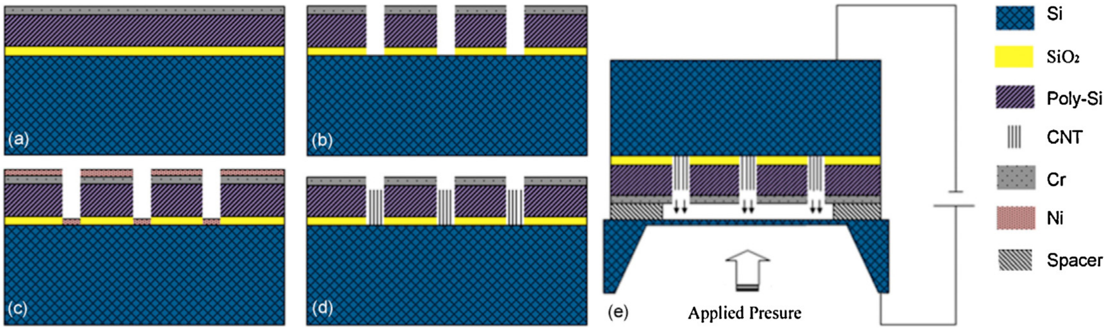

Fig. 1. Schematics of the cathode fabrication process: (a) The deposition of Cr/poly Si/SiO$_2$ layers on the substrate, (b) creating appropriate holes for CNT growth through vertical etching of poly-Si layer, (c) deposition of the nickel layer as the catalyst for CNT growth, (d) growing vertically aligned CNTs within the holes, (e) schematic of the fabricated field emission based sensor.

anode–cathode spacing has been also decreased in the fabrication process to improve the sensitivity and emission current level, while lowering the working voltage as well. The fabricated pressure sensor is a promising candidate for high sensitive, thermally stable pressure sensors.

2. Fabrication process

A 0.3-μm thick thermal silicon dioxide layer was grown on the wafers at 1050 °C after ⟨1 0 0⟩-oriented silicon wafers were cleaned in a standard RCA#1 solution. Fig. 1 schematically depicts the different stages of cathode fabrication process. A polysilicon layer was then deposited using low pressure chemical vapor deposition (LPCVD), with the thickness of about 2 μm. This layer was etched to realize micro holes to surround the CNTs in the final cathode structure. The deposition was carried out in the presence of SiH$_4$ and H$_2$ gases with the flow rates of 100 and 15 sccm, respectively. The temperature was set at 670 °C while the base pressure was 12 Torr during deposition. A 100 nm-thick layer of chromium was then deposited on the samples using e-beam evaporation while the base pressure was 5×10^{-6} Torr and the substrate temperature was 100 °C (Fig. 1a). Afterwards, the samples were patterned using standard lithography method and the chromium inside the windows was removed by wet etching. The samples were then put in a deep reactive ion etching (DRIE) system to undergo the vertical etching process to etch the polysilicon layer. This process consists of sequential etch and passivation processes that were respectively carried out by SF$_6$ plasma and H$_2$/O$_2$ plasma. More details on the vertical etching process can be found elsewhere [10]. The previously deposited Cr layer protects the underlying Si during this procedure. The samples were then dipped in 10% HF solution to remove the bottom oxide layer, the result of which is displayed in Fig. 1b.

An 8-nm thick nickel layer was also deposited by e-beam evaporation to serve as the catalyst layer in the subsequent step, the CNT growth (Fig. 1c). Vertically oriented CNTs were grown by PECVD. For this purpose, the samples were placed in the PECVD chamber and annealed at 650 °C for about 15 min in H$_2$ environment. The samples were exposed to H$_2$ plasma with power density of 5 W/cm^2 for 7 min. As a result, the nickel layer turns into nano-islands with an average diameter of about 50 nm. In the next step, the CNT growth started by introducing acetylene into the chamber, as the hydrocarbon gas species. The growth step continued for about 8 min to achieve 2 μm long CNTs. The flow rates of H$_2$ and C$_2$H$_2$ were respectively set at 20 and 6 sccm during the growth step. Fig. 1d shows the fabricated cathode structure with vertical CNTs grown inside the micro-holes. The presented cathode structure protects the CNTs from mechanical destruction during sensor operation and makes it possible to reduce the anode–cathode spacing and achieve high sensitivity, while maintaining output stability and repeatability. The screening effect that can suppress the field emission efficiency can be simply controlled by appropriate patterns of holes in this approach.

A silicon membrane was used as a flexible anode for the fabricated field emission sensor. Standard back-side micromachining in KOH solution was applied in order to fabricate the membrane. The thickness of the fabricated membrane was about 25 μm. Schematic of the fabricated field emission based pressure sensor is demonstrated in Fig. 1e. The prepared Si membrane was bonded against the fabricated CNT-based cathode. It can be observed that a spacer is placed between the anode and cathode in order to separate the electrodes and provide electrical isolation. The thickness of this spacer determines the effective anode–cathode interspacing in the fabricated sensors.

3. Operating principles

The sensor operation is based on monitoring the emission current from the grown CNTs (cathode) at a constant voltage, while the applied pressure deflects the flexible anode and causes consequent variation in the applied electric field. In other words, the pressure induced deflection of the membrane is the key parameter that determines the applied electric field value, and directly influences the emission current. Hence, to clarify the effects of different structural parameters of the fabricated sensor (Fig. 1e) on the output sensitivity, one should consider two main features: (i) the effect of the applied pressure on the membrane deflection; (ii) the variation of the emission current as a result of the membrane deflection. To elaborate on the first feature, we can assume the membrane as a one-dimensional beam, which is clamped at both ends (i.e., $y(x = 0) = y(x = L) = 0$) and is loaded by a uniformly distributed force (see Fig. 2). For the sake of simplicity, we have assumed a uniform anode–cathode spacing equivalent to the spacing at $x = L/4$, when

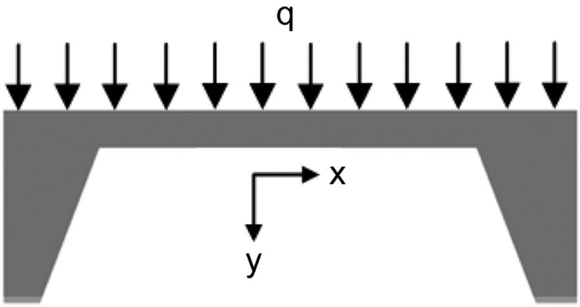

Fig. 2. Schematic of the membrane cross section as a one-dimensional beam, which is clamped at both ends and is loaded by a uniformly distributed force.