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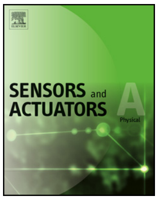

Electrical and thermal insulation via an oxidized, rough contact interface for the electro-thermal actuation of carbon nanotubes

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Two separated silicon structures in the shape of a hook and a T-bar are patterned by the Bosch process, and connected to a suspended carbon nanotube and an electro-thermal actuator, respectively. The contact interface between these two structures can provide electrical and thermal insulation when the nanotube is strained by the actuator. The rough etched silicon side walls significantly reduce physical contact area, resulting in a point-contact-like thermal conductance of 105 nW/K. A simulation result indicates that, when the temperature of the T-bar (actuator side) is increased by 191 K, the increased temperature of the hook (nanotube side) is less than 2.5 K. Using the native oxide on the silicon surfaces and symmetrically biasing the actuator, the nanotube is electrically insulated from the actuator. In addition, the gap between the T-bar and the hook can buffer the stress-induced mechanical deformation of the actuator during release so that the suspended nanotube will not be over-strained or damaged. Reproducible transport measurements of strained suspended nanotubes are demonstrated. Hence, this device architecture avoids rupture of the nanotube during release. Moreover, it also prevents the nanotube from being electrically or thermally coupled with the actuator during measurements.

1. Introduction

The electro-mechanical properties of carbon nanotubes (CNTs), e.g. strain dependent transport measurements, have been investigated by precision AFM indentation [1,2]. By integrating suspended CNTs into MEMS actuators, the AFM indentation can be replaced by on-chip MEMS actuation [3,4]. An electro-thermal bent-beam actuator is a promising candidate for straining CNTs. It can output large forces (∼2.5 mN) as well as large displacements (∼20 μm) at low driving voltages (5–12 V) [5], and it occupies a relatively small area [6]. Additionally, high precision displacement control of the thermal actuator was demonstrated [7]. Hence, electro-thermal actuation has been commonly employed in straining nano-structures [7–11]. However, heat generated in the thermal actuator could influence the devices under test, i.e. CNTs. Heat sinks were integrated into the actuation system to route the heat to the substrate [8,11], but the required power for the same output performance was increased.

In addition, the CNT under test needs to be electrically insulated from the actuator. Thus, the measurement of the CNT current modulation by strain is not coupled with the actuation voltages/currents. Electrical insulation between two conductive parts can be achieved by using an insulation layer [12–14]. However, it is challenging to avoid the insulation material from being etched by hydrofluoric acid (HF) during release. Alternative concepts are reported in literature. Silicon blocks are electrically separated by etching trenches through the Si device layer of a silicon-on-insulator (SOI) wafer. The two Si blocks can be mechanically connected via preserved buried oxide and handle layers [15] or via an additional electrically insulating epoxy [16]. In these approaches, backside through Si etching (to make the connection structure movable) or sequential post-process gluing is required.

In addition to the application of electrically insulating materials, the center of the actuation system is virtually set to 0 V by symmetrically biasing a symmetrical device structure [7,8]. Hence, the tested specimen, located at the center of the device, is not influenced by an increased actuation voltage. However, the fabrication of micro-structures always suffers from process tolerances. Consequently, the center voltage might deviate from the ideal 0 V.

Here, we propose a simple mechanical configuration to improve both the electrical and thermal insulation. The structures of this configuration can easily be fabricated, and no deposition process of an additional insulation layer is required. In addition, a contact interface with an ultra-low thermal conductance in this mechanical configuration suppresses the heat flux. Hence, the increased temperature of the CNTs under test is minimized while driving the actuator. Different from the method of dissipating heat to the

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substrate via additional heat sinks, this approach confines the heat in the actuator; this keeps the power consumption of the actuator low.

2. Working mechanism

The mechanical configuration consists of two separated Si structures, as shown in Fig. 1a. The hook structure is connected to the suspended CNT, while the T-bar structure is connected to the actuator. When the displacement of the actuator is larger than the gap between the hook and the T-bar, the T-bar will pull the hook, and the actuation force will be applied to the CNT. Except for force, voltage and heat are insulated by the contact interface. The working mechanism is detailed as follows.

2.1. Electrical insulation

A native oxide layer is formed after release on the surfaces of the Si hook and T-bar in ambient air. This thin oxide can electrically insulate the two structures when they are in contact. The maximum sustainable voltage of the oxidized contact interface depends on the oxide thickness and its electrical breakdown field, ~10 MV/cm [17]. Provided that the thickness of the native oxide on each side wall is 1 nm, the breakdown voltage of the contact interface is approximately 2 V. To minimize the voltage difference between the T-bar and the hook, the bent-beam actuator is biased symmetrically, namely applying two actuation voltages with two identical amplitudes but opposite polarities, as shown in Fig. 1b. Therefore, the potential of the T-bar is ideally 0 V. In addition, the hook serves as the drain electrode of the integrated CNT field effect transistor (CNTFET), and it is electrically grounded. Consequently, the voltage difference between the hook and T-bar is minimized, and the thin native oxides can insulate a voltage difference caused by an imperfection in the symmetry of the actuator structure.

2.2. Thermal insulation

The native oxide not only serves as an electrical insulation layer but also reduces the thermal conductance at the contact interface. According to the investigation in [18], a thin native oxide at the interface can reduce the thermal conductance by at least 50%. In addition, the hook and T-bar are patterned on an SOI chip by the Bosch process. The scallops on the side walls significantly reduce the contact area and consequently suppress heat conduction through the interface. The heat transfer through the interface is quantitatively analyzed in Section 4.3 based on measurement results.

2.3. Mechanical buffering

In addition to the electrical and thermal insulation, the structure also provides mechanical buffering for the integrated suspended CNTs. Due to mechanical amplification of the bent-beam actuator, a small elongation of the bent-beams results in a large displacement of the actuator. This is the working mechanism of bent-beam actuators. However, this mechanism also amplifies the undesired deformation caused by the relaxation of compressive thin film stress of the SOI device layer during HF release. The residual stress could be as high as hundreds of MPa [19]. To avoid the suspended CNT being over-strained by the deformation during release, the gap between the hook and the T-bar can serve as buffering space. Similar designs for mechanical buffering were also reported in literature [14,20,21]. The minimum required gap size depends on the residual stress and the actuator dimensions. Take the measured residual stress and actuator design for example: The maximum measured stress of the SOI device layer is -24 MPa, the bent-beam is 175 μm long, 2 μm wide, 4.5 μm thick, and the inclined angle is 2°. The stress-induced displacement is then approximately 0.5 μm. Without the buffering space, a suspended CNT, which is shorter than 10 μm, will be strained over its fracture strain of 5.3% [22].

The buffering space is especially important for CNTs grown on a thermal actuator before release. This is because the integrated CNTs are inevitably involved in the stress relaxation procedure during the HF release.

3. Fabrication process and results

The structures of the insulation configuration can be fabricated together with the thermal actuator and suspended CNTs by applying our previously developed CNT-MEMS integration process [23]. Silicon structures, including the hook, T-bar, bent-beam actuator, and Si bridges, are patterned by the Bosch process on the SOI device layer. The following oxidation and mechanical polishing converts the Si bridges into fully oxidized and flat bridges. CNTs are grown on the oxide bridges. An Al_2O_3 layer of 40 nm is deposited by low temperature atomic layer deposition (ALD) at 150 C to protect the as-grown CNTs from resist contamination during the structuring of the CNT metallization. Metal contact windows are opened into

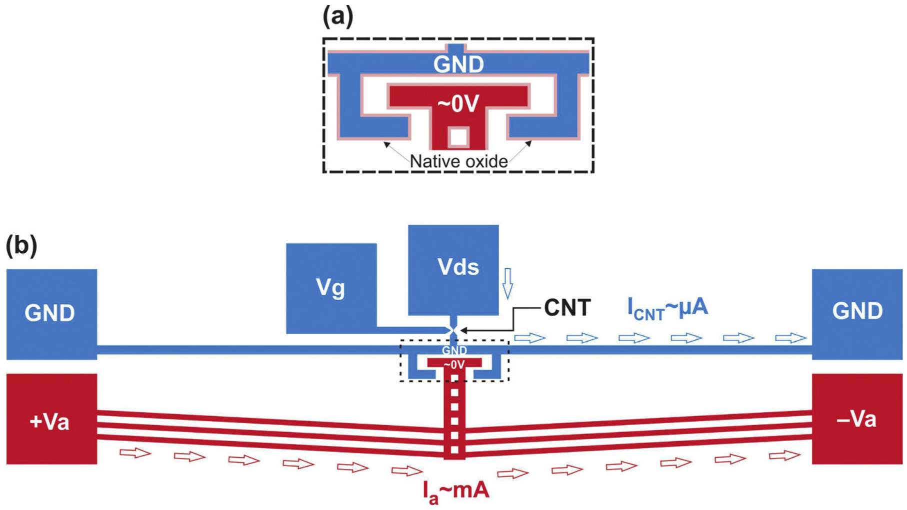

Fig. 1. (a) Mechanical structures of the hook and T-bar with native oxide; (b) schematic diagram of the voltage assignment of a CNT-MEMS device with symmetrical biasing. The two electrical currents, one passing through CNTs (I_{CNT}) and the other through the actuator (I_a), are separated by the native oxide.