DEVELOPMENT OF A 3D DISTRIBUTED CARBON NANOTUBES ON FLEXIBLE POLYMER FOR NORMAL AND SHEAR FORCES MEASUREMENT

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ABSTRACT

This study reports a simple approach to implement a flexible CNTs tactile sensor to enable the detecting of normal and shear forces. The merits of the presented tactile sensors are as follows, (1) embedded patterned CNTs into polymer using simple Si-substrate molding process, (2) 3D distributed CNTs enable the detection of shear and normal forces, and (3) 3D polymer structure by molding as a tactile-bump. In applications, the CNTs are grown and patterned on bulk-micromachined Si substrate with 3D surface profile. After polymer molding, the 3D distributed CNTs are successfully transferred onto a flexible PDMS with 3D tactile-bump. With proper CNTs pattern designs, the tactile sensor has a sensitivity (linearity) of up to 20.95%/N (R^2=0.93) for normal load, and up to 95.24%/N (R^2=0.95) for shear load.

INTRODUCTION

Tactile sensors have extensive applications in robot fingers sensing, human body weight measurement and human prosthetics. There are various novel designs and fabrication processes have been developed to implement the tactile sensor, for instance, the silicon-based process [1-2], such as bulk micromachining and CMOS processes, and non-silicon-based process, such as the polymer process [3-5]. In most cases, the requirement of tactile-bump leads addition processes. There are various post-processes have been developed to fabricate the polymer tactile-bump, such as the polymer dispensed [1], and polymer bonding approach [4]. The silicon rod structure made by alkaline etching [6] has been employed to act as tactile-bump. However, it is still not straightforward to integrate tactile-bump on tactile sensor substrate.

Carbon nanotubes (CNTs) show unique chemical, mechanical and electronic properties, and can be integrated with micro-electromechanical systems (MEMS) devices [7-10]; for instance, the integration of patterning CNTs on a highly MEMS structured 3D substrate surface [8] and the integration of suspended CNTs with MEMS devices [9] has been successfully demonstrated. Thus, the integration of CNTs and MEMS can find several applications. The integration of CNTs with existing micro-fabrication process is critical concerns for these applications.

This study presents a simple process to realize a CNTs-based flexible tactile sensor to measure normal and shear forces. This study employs various approaches, including direct deposition, contact printing, and shadow mask techniques, to define the 3D CNTs patterns on a bulk micromachined Si substrate. After the polymer molding process, the 3D CNTs patterns are transfer to a flexible substrate to form the CNTs-based flexible tactile sensor. Moreover, the bulk micromachined cavities on Si substrate enable the formation of tactile-bumps after polymer molding. Thus, additional process for tactile-bump is not required.

CONCEPT AND FABRICARTION

Fig.1 shows the concepts of the presented flexible CNTs tactile sensor. In short, the CNTs pattern is distributed on a polymer substrate with tactile-bump. The loading on tactile-bump will lead to the deformation of the CNTs pattern and further cause the resistance change. Thus, the load can be measured through the variation of the resistance. Fig.1 shows six different designs in this study, (1) Fig.1a-b: the CNTs distributed on the whole flexible substrate surface with tactile bump, (2) Fig.1c: the CNTs distributed on the whole bump (defined by isotropic etch), (3) Fig.1d-f: the 3D CNTs patterns on the bump (defined by anisotropic etch).

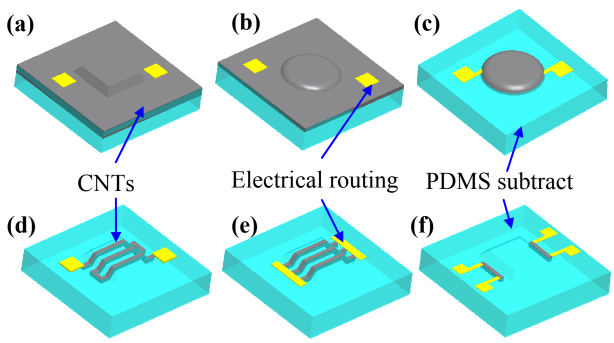

Fig.1: The concept of CNTs on PDMS substrate with native bump.

This study establishes the processes in Fig.2 to implement the present tactile sensors. In Fig.2a, the silicon substrates were fabricated by bulk-micromachined processes to define the 3D shapes of CNTs sensing elements and the tactile-bumps. In Fig.2a1 and Fig.2a3, the silicon substrates were etched anisotropically by KOH etchant at 80°C. In Fig.2a2, the silicon substrate was etched isotropically by HNA at room temperature. These anisotropic and isotropic etched cavities acted as the 3D-mold to form tactile-bumps during the following polymer molding process.

After that, the Fe film was deposited and patterned on Si-substrate with 3D surface to act as the catalyst layer for the growth of CNTs, as illustrated in Fig.2c. The direct deposition approach in Fig.2b1 was employed to realize the concept illustrated in Figs.1a-1b. The contact printing approach in Fig.2b2 was employed to realize the concept illustrated in Fig.1c. The photoresist was transferred from glass onto Si-substrate for contact printing approach in Fig.2b2, and then Fe catalyst layer was patterned by lift-off process. The shadow mask approach in Fig.2b3 was employed to realize the concept illustrated in Figs.1d-1f. The shadow mask was fabricated using the laser micromachining on a steel sheet. The minimum line width of the shadow mask was 50μm for a 250μm thick steel sheet. Thus, the 3D CNTs patterns in Figs.1d-1f were defined.

As illustrated in Fig.2c, the CNTs were then grown on the surface of the bulk micromachined cavities using the acetylene pyrolysis at 800°C in a gas mixture of Ar, NH_3, and C_2H_2. Moreover, the molding process was employed to transfer the 3D distributed CNTs onto flexible PDMS-substrate, as shown in Fig.2d. During the molding process, the PDMS was poured onto the 3D-mold-substrate, and the air trapped inside the cavity was fully removed by vacuum pump. The molded PDMS attached to the mold substrate was cured at 100°C for 1 hour. Thus, the polymer bump for tactile sensor was realized. Finally, the metal film was selectively deposited on 3D distributed CNTs with PDMS substrate surface as electrical routing through shadow mask, as in Fig.2e.

RESULTS AND DISCUSSION

As demonstrated in Fig.3, the 3D distributed CNTs on the anisotropic or isotropic etched cavities surface were fabricated using the processes shown in Fig.2a-d. The FE-SEM (field emission scanning electron microscope) micrographs in Figs.3a-3b respectively show the CNTs distributed on the whole 3D silicon surface with anisotropic and isotropic etched cavities using the processes illustrated inFigs.2a1-d1. The SEM micrograph in Fig.3c shows the patterned CNTs on the whole isotropic etched cavity, and it was defined by contact printing of Fe catalyst layer approach using the processes shown in Fig.2a2-d2. In Figs.3d-3f, the 3D patterned CNTs on the anisotropic etched cavities surface were defined by shadow mask of Fe catalyst layer approach using the processes shown in Fig.2a3-d3. Thus, various 3D patterned CNTs on Si mold-substrate were realized.

Moreover, the optical images in Fig.4 exhibits the successful transfer of 3D CNTs (black) patterns onto the flexible PDMS (transparent) with tactile-bump using the processes shown in Fig.2d. Various tactile bumps have been realized using the mold transfer process. The 3D CNTs sensing patterns can be clearly observed in the optical images of Fig.4 sincethe PDMS substrate is transparent. Finally, the optical images in Fig.5 present the 3D patterned CNTs deposited with metal pads on flexible PDMS substrate surface using the process in Fig.2e. The metal pads were employed to measure the resistance change of those CNTs-based flexible tactile sensors.

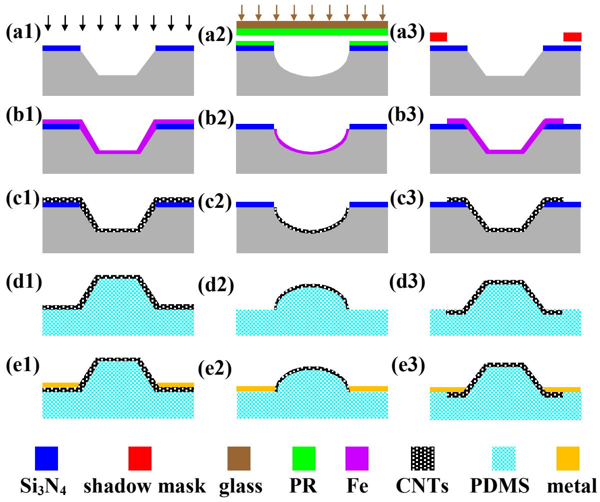

Fig.2: The fabrication process flow to for defined CNTs PDMS substrate with native bump.

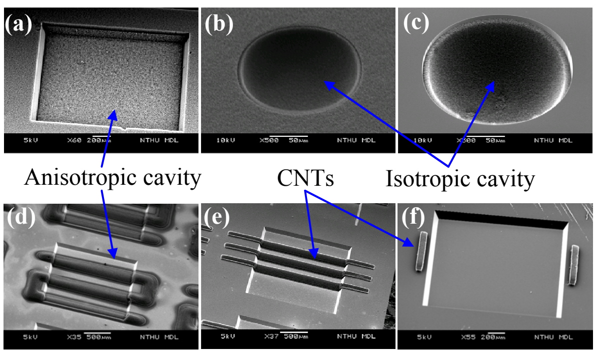

Fig.3: The FE-SEM micrograph of typical fabrication results containing CNTs-patterns of Si-mold substrate.

In short, the shapes of the tactile-bump are defined by the bulk micromachined cavities on Si substrate. Due to the bulk-micromaching and molding processes, a tactile-bump is naturally formed on the flexible CNTs tactile sensor without any additional complicated process. Moreover, the in-plane dimensions (length and width) of the 3D CNTs sensing patterns can be easily tuned using the photolithography and shadow mask approach. The height of 3D CNTs sensing patterns can be modified by varying the etching depth of cavity. Thus, the fabrication process allows the changing of tactile-bump dimension and CNTs patterned easily. The sensing range of the present flexible CNTs tactile sensor can be easily tuned.

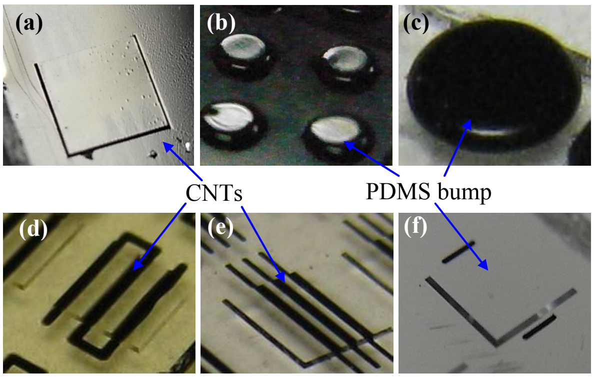

Fig.4: The optical images of typical fabrication results containing CNTs-patterns of PDMS substrate.

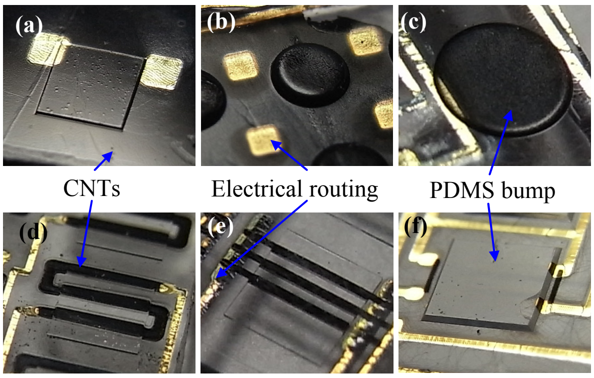

Fig.5: The optical images of typical fabrication results containing metal pads deposited on CNTs-patterns of PDMS substrate.

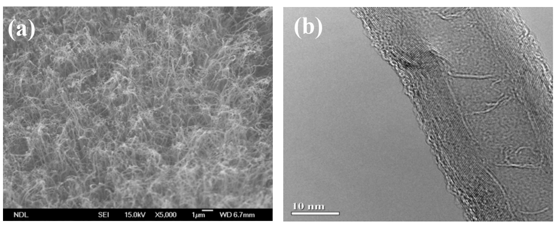

Fig.6: The (a) FE-SEM micrograph and (b) TEM image for the nanostructure of CNTs.

The CNTs grown from the present processes were characterized using the field emission scanning electron microscopy, and the TEM. The FE-SEM image in Fig.6a exhibits the tubular nanostructure and the net of nanotubular chains of CNTs. The TEM image in Fig. 6b shows that the CNTs are multi-walled with bamboo-like structure. The average diameter of CNTs is about 20-30nm. The test setup in Fig.7, including micro-force gauge, source meter, and position stages, was established to characterize the performances of present 3D distributed CNTs tactile sensors. The micro-force gauge with 1mN resolution was used to apply load on the tactile sensor. The resistance change of the tactile sensor was recorded by the source meter.

Measurements in Fig.8 show the variation of resistance change (ΔR/R) after applying a normal force (ranging from 1N to 6N) on the tactile sensors shown in Fig.5a-b. In these two cases, the CNTs covers on the whole PDMS surface including tactile-bump. The shapes of tactile-bump are respectively molded form the cavities fabricated from the anisotropic and isotropic etchings. The sensitivity (linearity) of these two tactile sensors is: 0.65%/N (R^2=0.96) for the design in Fig.5a, and 0.49%/N (R^2=0.98) for the design in Fig.5b. Fig.9 also shows the variation of resistance change (ΔR/R) as the normal force applying on the tactile sensors with patterned CNTs on tactile-bump. The four different samples, as shown in Fig.5c-f, are respectively characterized in the tests. The sensitivity (linearity) of these three tactile sensors with patterned CNTs is: 20.95%/N (R^2=0.92) for the design in Fig.5c, 9.27%/N (R^2=0.99) for the design in Fig.5d, 2.67%/N (R^2=0.99) for the design in Fig.5e, and 22.76%/N (R^2=0.97) for the design in Fig.5f. In comparison with the results in Fig.8, the sensitivity is improved by using the samples with patterned CNTs on tactile-bump. This study also investigates the variation of ΔR/R after applying a shear force (from 0 to 0.10N) on tactile sensors. The preliminary measurement results in Fig.10 show the sensitivity

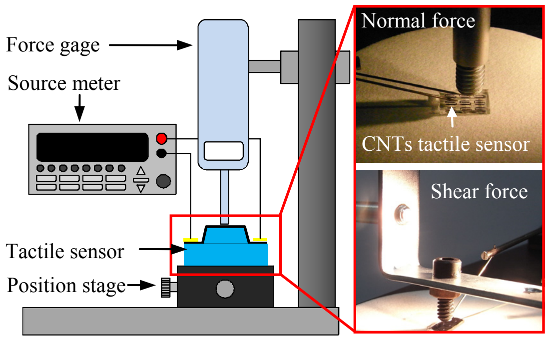

Fig.7: The optical image of three-axis force measurement setup for applying normal and shear force to the bump.

(linearity) of three tactile sensors are: 53.68%/N (R^2=0.94) for Fig.5a, 95.24%/N (R^2=0.95) for Fig.5b, and 18.18%/N (R^2=0.98) for Fig.5f. However, the measurement results are not available for the designs in Figs.5c-e. Moreover, the shear force sensitivity of the designs in Fig.5a-b is too high. More tests are required to confirm the performance of sensors.

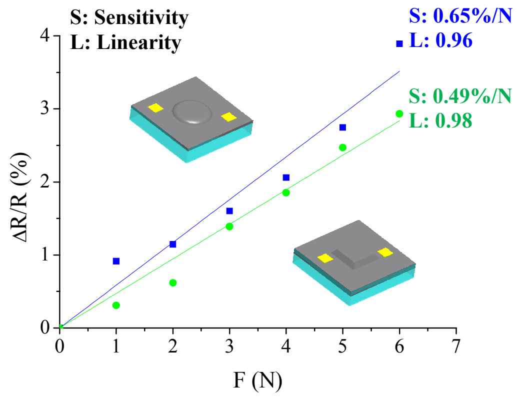

Fig.8: The measurement results to show the variation of resistance change with normal load in CNTs covered on the whole tactile-bump.

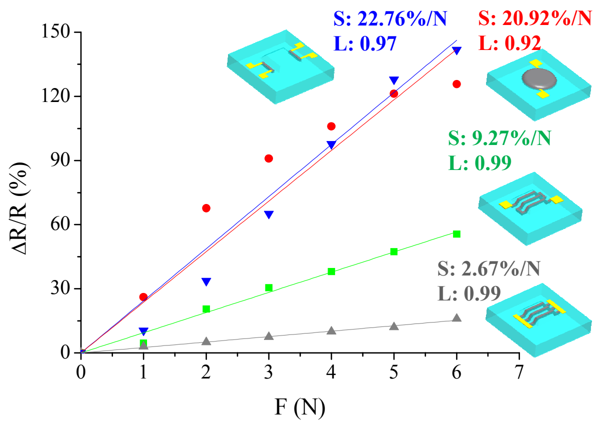

Fig.9: The measurement results to show the variation of resistance change with normal load in the patterned CNTs on tactile-bump.

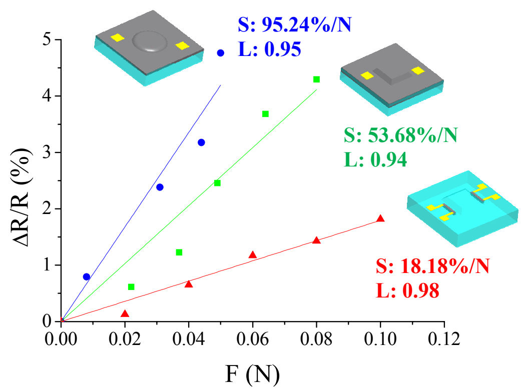

Fig.10: The measurement results to show the variation of resistance change with shear load in CNTs covered on the whole tactile-bump.

CONCLUSIONS

In summary, this study has successfully demonstrated a simple approach to implement a flexible CNTs tactile sensor enable the detecting of normal and shear forces. Due to the simple bulk-micromachining and molding processes, a tactile-bump is naturally formed on the flexible CNTs tactile sensor without any additional complicated process. Moreover, the fabrication process allows the changing of tactile-bump dimensions and CNTs pattern easily, so as to further tune the sensing range and sensitivity of the present flexible CNTs tactile sensor. In applications, the tactile sensors with various 3D CNTs patterns and different polymer tactile-bumps are demonstrated. With a proper CNTs pattern design, the tactile sensor has a sensitivity of up to 22.76%/N (with a linearity of R^2=0.97) to the normal load and up to 95.24%/N (with a linearity of R^2=0.95) to the shear load. However, more shear force tests are required to evaluate the performance of tactile sensor.

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