Application of VACNTs in MEMS devices

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ABSTRACT

Vertically aligned Carbon Nanotubes (CNTs) which are commonly referred to as CNT forests, have many potential engineering applications for its attractive mechanical, electrical, optical, and thermal properties. Various micro patterning of VACNTs are used for fabricating MEMS devices such as pressure sensor, thermometer, switches etc. A new patterning technique recently introduced by our group is named as micro mechanical bending (M2B) of VACNTs. Typically, CNT forest is known to be the darkest material on earth that can almost completely absorb light. This new M2B technique for CNT forest remarkably changes the optical property of the processed zone. The most significant observation made from the processed CNT forest is the visible optical reflection from bent and flattened area. Another interesting property of the resultant is anisotropic behaviour of the surface. The anisotropic and flexible nature of CNT forest has opened the gateway to use these patterned CNT forest as several types of MEMS based sensor, which will be discussed in this paper.

Keywords: Carbon Nanotubes Forest, micro-mechanical bending (M2B) method, post-growth processing technique, MEMS etc

1.0 INTRODUCTION

CNT forests are found to be having excellent physical, electrical, thermal and optical properties, thus theoretically useful in micro-electro-mechanical systems (MEMS) design. In order to materialize the conceptual, CNT forests need to be prepared with determined properties and arrangement. Growing technique and post growth technique need to be established for the production of well consistent shape and geometry for all finished pattern. Micro-patterning is a post processing technique for the structural modification of CNT forests before being incorporated into device configuration. There are list of techniques to perform micro-patterning, each with its own credibility. Controllable vapour densification which reported by Jiang and Weng et al. (Jiang, Wang, Chen, Ye, & Liu, 2013; Wang et al., 2012), has been shown a feasibility to modify the structure using solvent by increasing the volume fraction of VACNTs using Acetone. Rubio et al. introduced electron beam cutting but it is very limited to individual CNT (Rubio, Apell, Venema, & Dekker, 2000). Then, Lim used laser to shape various structures (Lim, 2003), but it is lacked of accuracy and control due to thermal damage. Zhu et al use arc discharge to pattern some shape, however the arc is very high in energy (Zhu, Sow, Sim, Sharma, & Kripesh, 2007) thus less in accuracy.

Latest development micro-electro-discharge machining (MEDM) still inherit spark gap problem (Khalid et al., 2010). Afterwards, the effort of improvement in the MEDM techniques was continued, first by reverse polarity of tool and workpiece, taking advantage of CNT as a good field emitter (Saleh, Dahmardeh, Bsoul, Nojeh, & Takahata, 2011). Then, the effort continued with replacing the normal air with high dielectric gas SF_6 (Saleh, Dahmardeh, Nojeh, & Takahata, 2013). Even though there is significant improvement, however the problem of spark gap still exists. Bending of VACNTs is first introduced by Saleh et al. (Saleh et al., 2012), but brief characterization has been done by (MA M Razib, T Saleh, 2014).

In this article, a new patterning method micro-mechanical bending (M2B) method and its potential in MEMS devices are introduced. Various parameters were assessed and the optimal parameter was identified. Subsequently optimal best parameter was employed to make a various shape and form of 3-D structures, to show its feasibility in MEMS construction.

The M2B method is different from the MEDM in term of mechanism and concept. MEDM is using voltage and capacitance to create spark to remove material at every pulse with energy of $CV^2/2$, where C is capacitance and V is voltage respectively. Whilst M2B method is solely mechanical with bending and entanglement of CNTs by a rotating tool to compact and flatten the surface.

CNT forests are well known as a super dark material (Mizuno et al., 2009). This behaviour is closely related to its low density array, high porosity, nanometer size of nanotubes, and random arrangement of surface profile (Yang, Ci, Bur, Lin, & Ajayan, 2008) (Fig. 1(a)). Interestingly, the M2B method could transform CNT forests from darkest material on earth to reflective mirror by two(2) order of magnitude.

2.0 EXPERIMENT DETAIL

The CNT forest samples were prepared on highly doped silicon substrates (<100> n-type, resistivity 0.008-0.015 Ωcm), using an atmospheric-pressure CVD system. The identified gas such as ethlyne, hydrogen and argon are mixed at certain ratio during growing procedure. The details of the preparation process with specific conditions can be found in (Saleh et al., 2012). The process yielded forests of vertically aligned multiwalled CNTs with lengths of up to several 100's of µm on several cm^2.

The experiment of micro-mechanical bending (M2B) method of the CNT forests were performed using a servo-controlled 3-axis Micro-CNC system (Mikrotools Ltd). This machine has capability of 1-µm sensitivity positioning resolution. To start, the electrode or tool is positioned just above the CNT forest while rotated (Fig. 1(a)). The tool (tungsten, diameter of 300 µm) was shaped at determined diameter centrally on the rotational axis using a method called wire-electro-discharge-grinding (WEDG). Then, the tool was programmed to move downward in Z-direction (also called as step size) before moving in lateral speed in X- and Y- direction. This technique will compact the CNTs (Fig. 1(b)) to follow the direction of rotated tool (Fig. 1(c)) and create a pattern on the bare CNT forest by the local mechanical manipulation of the CNTs. Tool rotational speed, X-Y lateral speed and step size in the Z direction were also varied, respectively, as per Table-1 below.

Table 1- M2B Method conditions used for CNT micro-patterning	
Rotational Spindle Speed (RPM)	50, 1000, 1500, 2000, 2500
Lateral Speed in X-Y Direction (mm/min)	1, 5, 10, 25
Step Size in Z-Direction (µm)	1, 5, 10
Total Depth (µm)	60, 100, 200, 300
Tool material	Tungsten
Tool size, diameter (µm)	300
Tool machining condition with WEDG	Tool 1 - 90 V, 13 pF; 5.265×10^{-8}J Tool 2 - 100 V, 10nF; 5×10^{-5}J Tool 3 - 110 V, 0.4µF. 2.42×10^{-3}J

The patterns are all characterized in order to determine the best parameter with smoothest surface. In the next phase, the speed was further varied at 5 mm/min and 10 min/min to see the effect of varying the tool's speed. Subsequently, the best parameter was employed at various total depth of bend at 100 µm, 200 µm and 300 µm. To see the impact of different tool topography at the CNT forests, voltage and capacitance are also varied, then we patterned with the best parameters. Lastly the best parameter was employed to pattern the 3D structures.

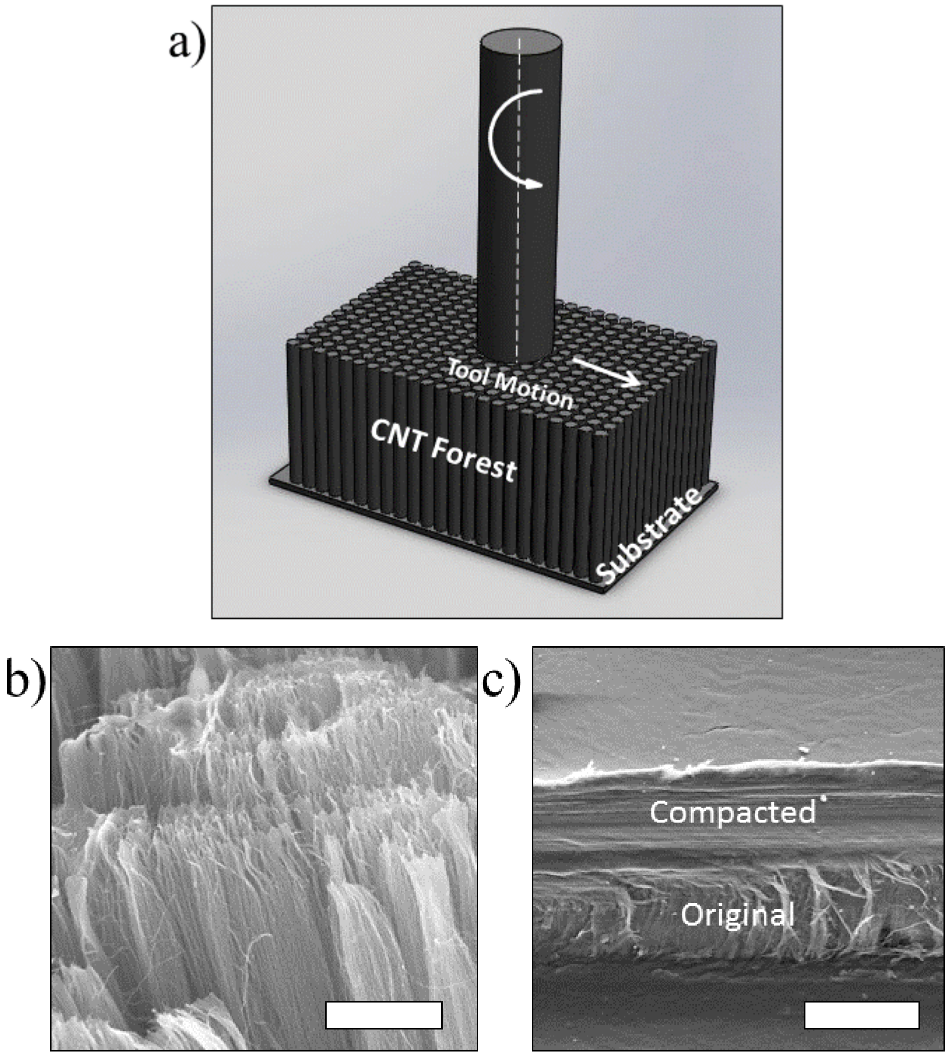


Figure 1 – a) Schematic diagram of M2B (Micro-Mechanical Bending) method. b) Field Emission Scanning Electron Microscopy (FE-SEM) images of bare CNT forests view from tilted angle 30^{o} on the side. The nanotubes are vertically aligned. Scale bar, 5 µm. c) FE-SEM image of CNT forest with portion being compacted. Scale bar, 15 µm.

3.0 RESULTS AND DISCUSSION

Light reflects off surface accordance to the law of reflection. When light falling upon the surface, it will be reflected back at the same angle with incident angle. This law will determine the specular reflection and diffuse reflection. For the smooth surface, light will reflect in bundle (Fig. 2(a)) whereas for rough surface, the light will diffuse and reflect in many difference directions (Fig. 2(b)). With low surface roughness, for example at 2000 rpm, 1 mm/min and 1 µm step size, the value of reflectance is the highest as compared to the other parameters as shown in graph below (Fig. 2(c)) with average surface value, R_a of 15 nm. The lowest value of reflectance is 77 % which is patterned with 1500 rpm, 1 mm/min and 5 µm step size, and average surface value, R_a obtained is at 29 nm. Some reading at some rpm shows different results from expectation due to unexpected crack occur, thus reduce the reflectivity. Step size does not have any effect on the flatten surface, but the crack could be propagated and spreaded to the flatten area.

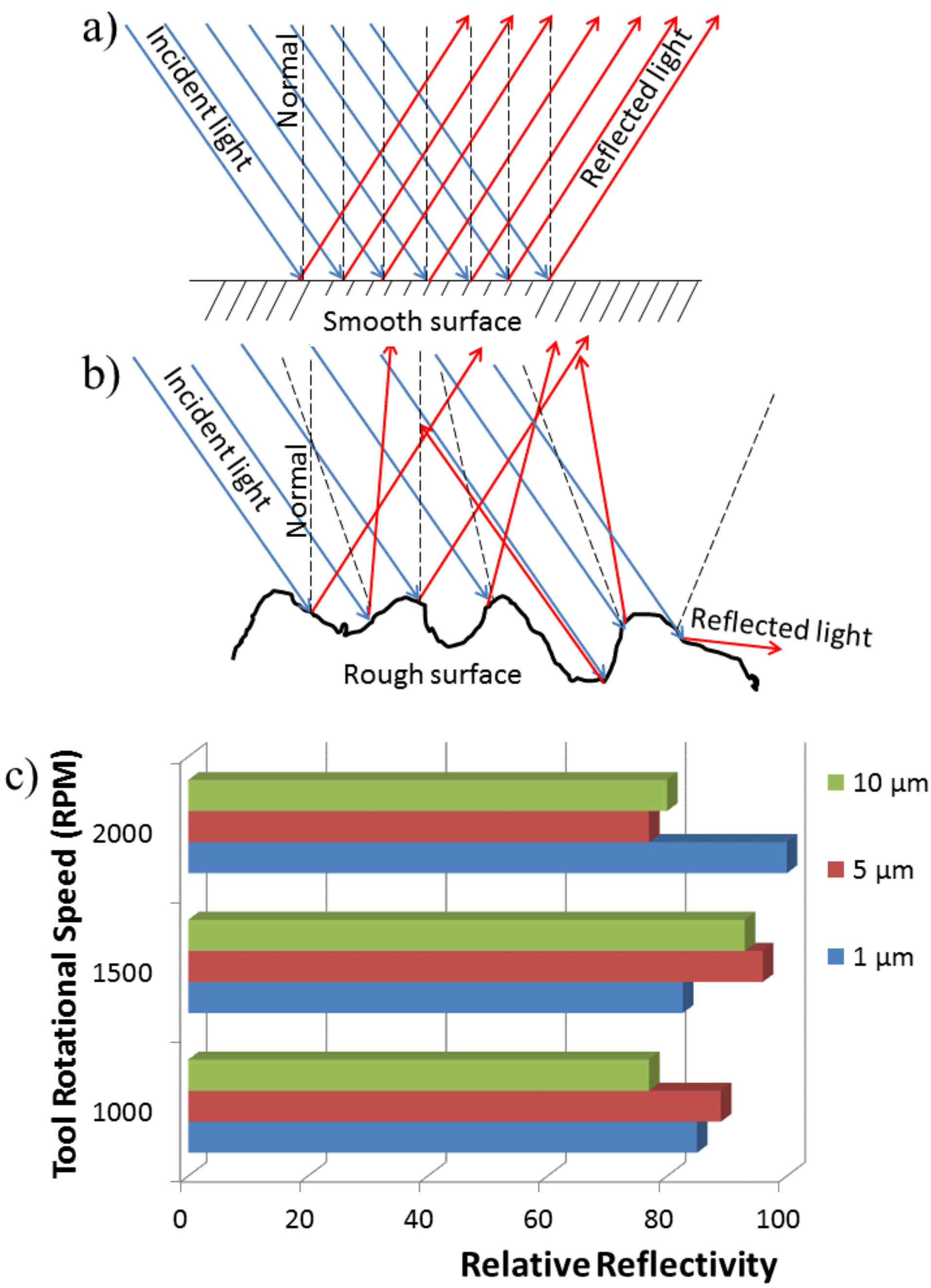


Figure 2 – a) Schematic diagram of specular reflection. b) Schematic diagram of diffuse reflection. c) Graph of tool rotational speed against reflectivity.

3.1 Ability to transform from naturally absorption to reflective

All this while, a forest of vertically aligned Carbon Nanotubes is only known for its highly absorption properties (Mizuno et al., 2009). At all wavelengths, very low reflectivity at 0.045% reflected back because of the low density, sparseness and imperfect alignment of CNT forests (Yang et al., 2008). However, T Saleh et al. has shown that CNT forests could also behave oppositely to become a mirror when compressed by a rotating tool (Saleh et al., 2012). By modifying the structural from top, it could compact the CNTs to follow the direction of the tool. As can be seen from Fig. 1(c), the compaction and compression of CNTs could make the holes being eliminated thus become the reason that light can't passed through the CNT forests (Fig. 1(c) as compared to Fig. 1(b)). The reason behind the observed phenomena is that by mechanical manipulation the top surface of the domestic region flattens texture of CNTs becomes smoother and overcome the porosity of the VACNTs. Also

CNTs grown are essentially metallic MWCNTs thus the reflection is more visible up to 10-15% (Saleh et al., 2012).

3.2 Properties of the resultant as anisotropic mirror

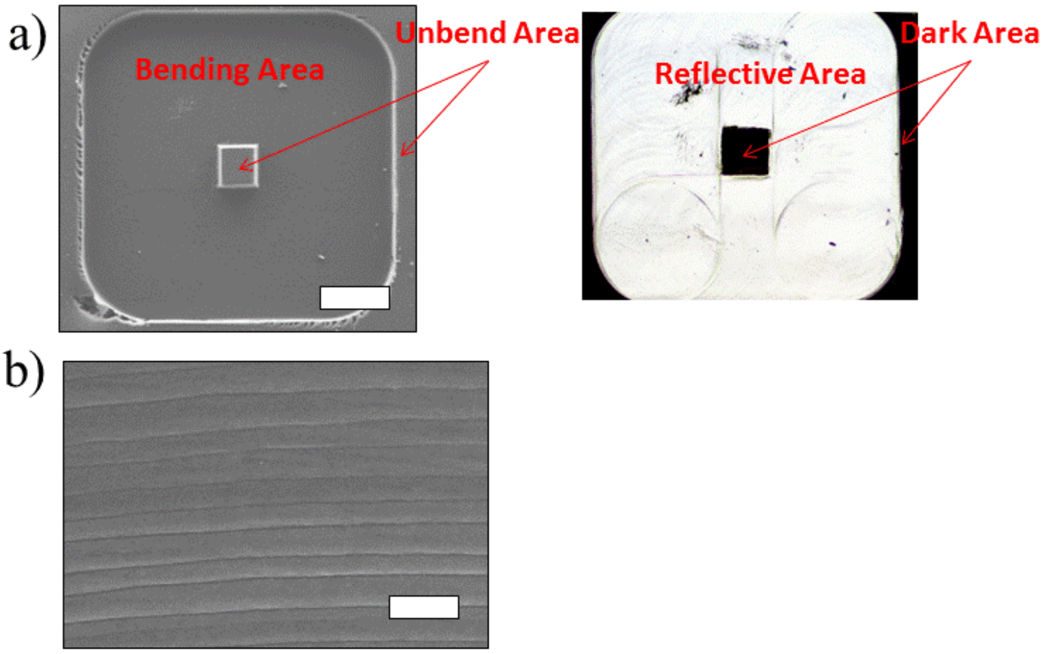
It is also noticed that the surface of the flatten area has periodically grating like pattern, which has caused diffraction phenomena (Saleh et al., 2012). He noticed that the processed surface not only reflective but also interestingly it diffracts white and blue light at different incident angle of light. This phenomenon could be caused by the rotation movement of the tool and micro-patterning parameters (rotational spindle speed and lateral bending speed). This alignment also could determine the surface roughness of the flatten area. All these achievements from the processed smooth texture were found due to the spiked alignment of VACNTs in to the resultant direction of the tool motion. The alignment could be useful in several ways; light diffraction, aligned MWCNTs polarizer and as angle sensor which will be described later.

3.3 Structural modification from 2D

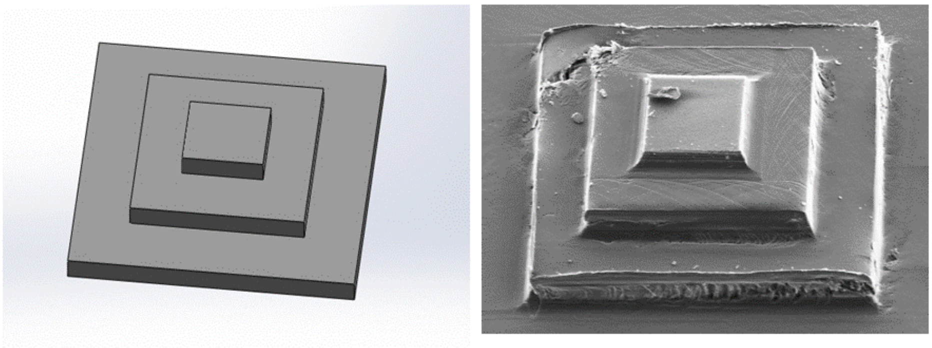
Structural modification of CNT forests is transforming bare CNT forests from having 2D structures over the surface into 3D structures with different height, width, shape and thickness etc. Movement of the rotating tool in X-, Y- and Z-direction with defined speed could compress the CNTs therefore flatten the surface according to the tool movement. The M2B method is necessary for the integration within MEMS design that having different configurations. Another interesting note is by having different form of tool, one could achieve different type of patterns (Fig. 3(c)).

Previously, various shapes and microstructures of CNT forest have been utilized for the fabrication of MEMS devices i.e. fuel cells (Kuriyama, Kubota, Okamura, Suzuki, & Sasahara, 2008), solar cells (Klinger, Patel, & Postma, 2012), wafer scale (Hayamizu et al., 2008), pressure sensor (Camilli et al., 2013) etc. The MEMS based strain sensor was also demonstrated using dog bone shaped of CNTs by Graphtec CE-5000. A list of technique has been applied to produce 3D structures; using both bottom up and top down technique, has been explained in introduction.

The M2B technique shows a potential in producing various structures having smooth texture which facilitate its appearance in various MEMS/NEMS applications. M2B method is showing its independent potentiality over the previous patterning methods.



c)



d)

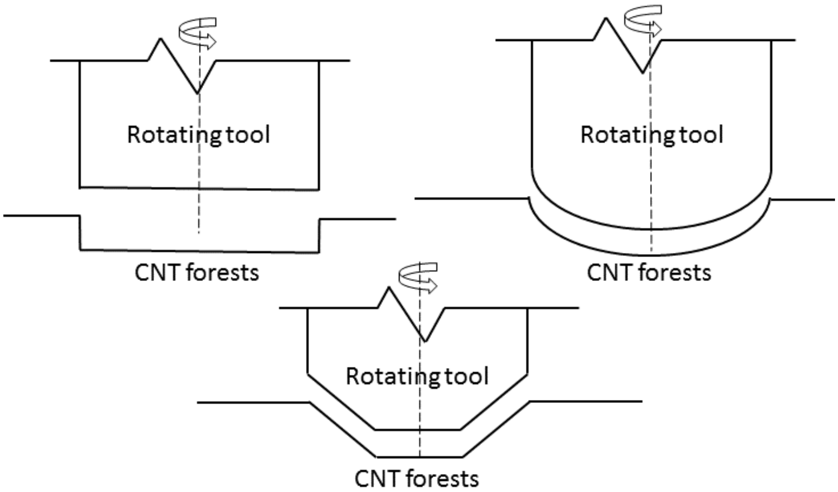


Figure 3 – a) FE-SEM image and its optical reflection of pattern with 2000 rpm, 1 mm/min, 1 μm. Scale bar 150 μm. reflective pattern b) Grating is visible cause by the tool c) 3 Step pyramid structure d) Different shape of tool caused different pattern shape.

4.0 POTENTIAL APPLICATIONS OF CNTS FROM M2B METHOD

After two decades of extensive investigation into the unique properties of carbon nanotubes (CNTs), the primary focus is now shifting toward the utilization of CNTs in real applications. In this paper we have presented the real potential application from the M2B method.

4.1 Linear Displacement Sensor

The M2B method is potentially known to transform processed VACNT forests as reflective mirror showing 10-15% reflection of incident light (Saleh et al., 2012). Through proper processing and fabrication this interesting phenomenon is applicable in producing monolithically integrated micro-scale reflector absorber arrays sensor. Figure 4(a) shows the process to measure linear displacement of a linearly displaced object by shooting laser on the patterned area of VACNTs. Figure 4(b) reveals about how the digitalised outcomes can be achieved according to the displacement of the linearly motion object. Figure 4(c) is patterned using M2B method.

The VACNTs are flexible by nature. If CNT forest is grown on a flexible substrate like thin Al sheet or flexible stainless steel, it could be attached on the rotating cylindrical object. 10-15% reflection is sufficient to be manipulated in producing micro and long range optical sensor to detect any changes in angular distance. Thereafter, by the same procedures as applied for linear displacement sensor the displacement of the angularly rotated object could be achieved as indicated in Figure 4(d).

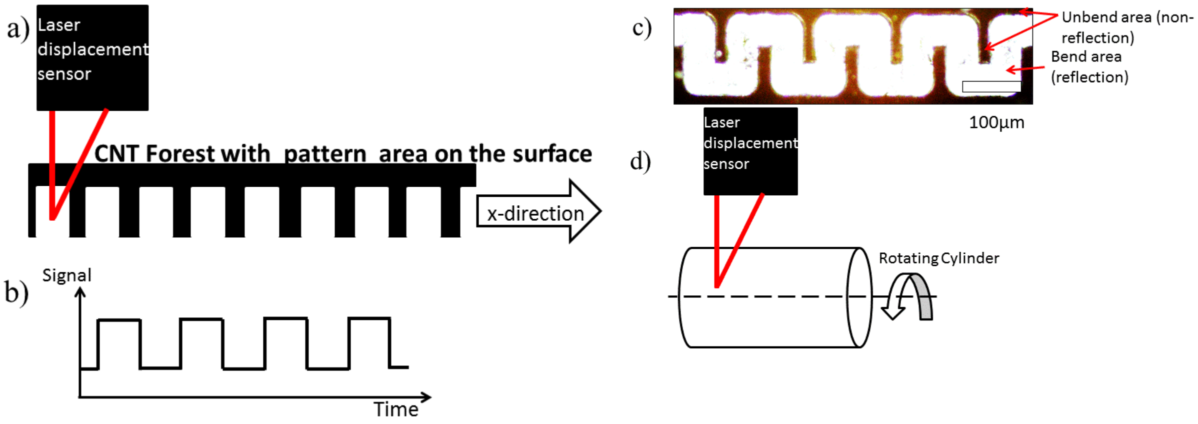


Figure 4 – (a) Conceptual diagram of the potential application of CNT forest as linear and angular encoder. As CNT forest is flexible therefore it can be used to measure both angular displacement and linear displacement if grown on a flexible substrate. b) Signal. c) Reflection from the patterned area compared to the bare CNT forest area (black area). d) Conceptual design on how if the CNT forests is growth on the flexible substrate and the substrate is rotated along its axis.

4.2 Angle Sensor

Normal light vibrates equally in all direction perpendicular to its path of propagation. If the light is constrained to vibrate in only one plane, however, we say that it is plane polarized light. The direction that the light vibrates is called the vibration direction, which for now will be perpendicular to the direction.

From this entire known characteristic we will employed patterned CNT forest to design analog angle sensor. Previous study shown that patterning of CNT forest by mechanical bending; optically transforms the material from darkest absorber to reflective mirror (Saleh et al., 2012). Very interestingly the reflectance of the flattened CNT region is dependent on the polarization direction of the incident light because of its anisotropic behaviour as mentioned earlier. We can shine a polarized light on the patterned CNT surface and measure the reflected light power. The reflected light power will vary as the sensor is rotated from 0 to 90 degree because this will change the incident polarization. Thus, we can calibrate the reflected power Vs degrees of rotation of the sensor.

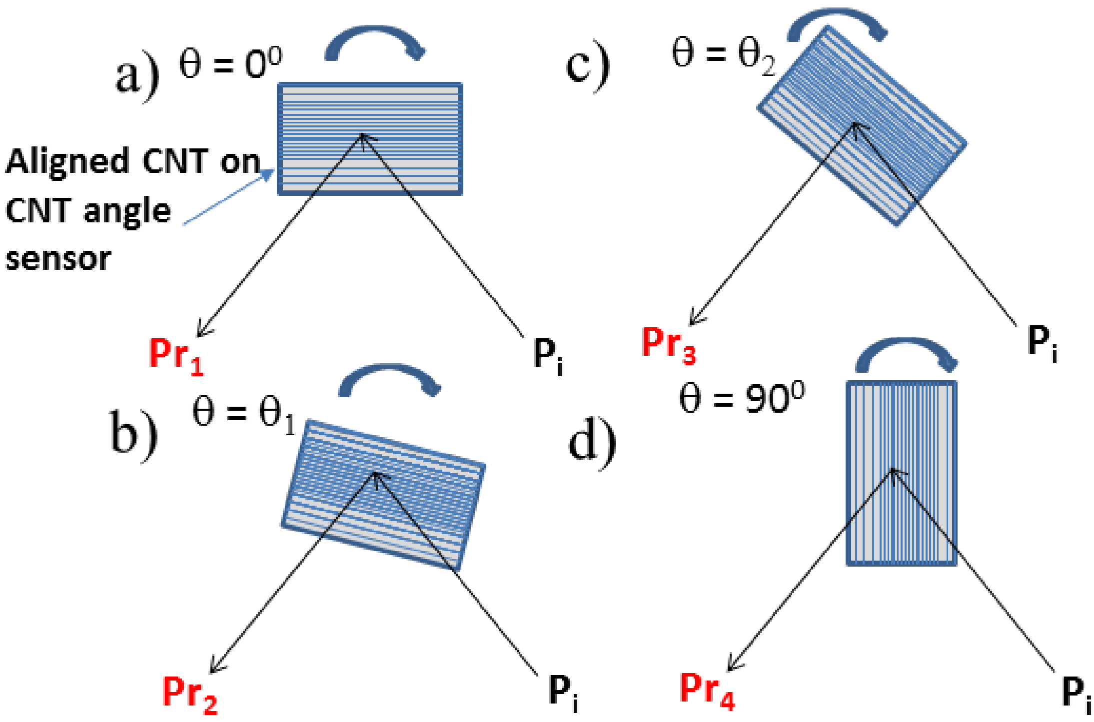


Figure 5 – Reflection of light will be measured at various angle of rotation a) 0_o b) Θ_1 c) Θ_2 d) 90^o. P_i = incident power of polarized light, Pr_i = reflected power from CNT angle sensor at Θ.

Characterization of the developed sensor shall be carried out by examining its sensitivity, linearity, repeatability, accuracy, frequency response and hysteresis. New type of angular displacement sensor will have the following property:

a) Measurement range is larger compared to other optical angle sensor. This can measure up to 90 degree tilt angle whereas conventional tilt sensor can measure up to ~30-60 degree.

b) Compactness as micron level fabrication is possible.

c) Easily available in chip form.

d) Passive type sensor so no extra circuitry is necessary. Can be designed for surface mount which can be easily attached to target object.

e) Contact less measurement is possible.

f) Sensing principle is based on the optical property of the CNTs, therefore it is not affected by electro-magnetic (EM) noise.

g) Filtering and signal conditioning circuit is not necessary.

This sensor can be useful for following applications:

i. To measure tilt angle for base adjustment for high precision machine assembly;

ii. To adjust the workpiece fixture for high precision CNC machining;

iii. To measure the tilt angle of robotic joints etc;

iv. To measure the micro lens orientation angle for biomedical applications.

4.3 Strain Sensor

CNT forests inhibit anisotropic properties. When polarized light impended onto the surface, in such that s-polarization, there will be power reflected back from the surface. When the flexible substrate is in concave position, more CNTs will be packed and compressed at the centre region. Thus, the density will be increased and more light will be reflected. This behaviour is contradicted when the flexible substrate in convex position, /CNTs will be dislodged apart thus when light fall onto the surface, more light will be reflected back.

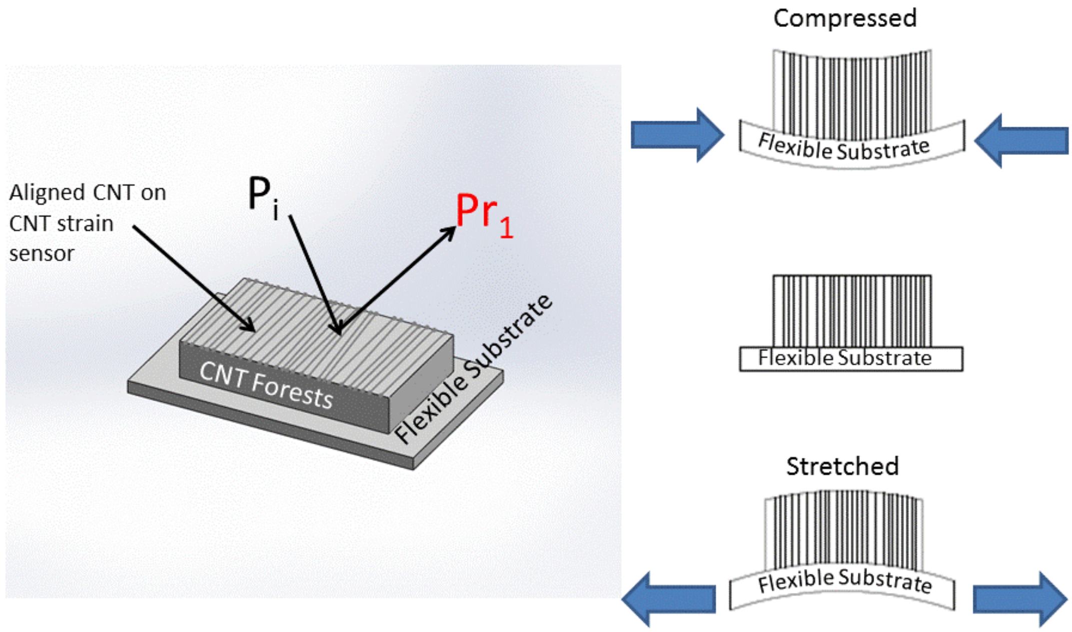


Figure 6 – Light will impeded onto the surface and reflected back (Left picture). CNT forests in compressed and expanded mode (Right image).

4.4 Micro concave mirror

Concave mirror is curved shaped reflecting surface mirror. It has many usage such as telescope, camera etc. Shape of the pattern will be determined by the tool geometry. When we have a tool with semi cylindrical end, it will be resulted in micro concave mirror with reflection. The surface is anticipated to be better due to less stress induced on the surface due to force direction is evenly distributed on the curve surface of the tool. Perfectly shape semi cylinder is required for the perfect shape of semi cylindrical.

5.0 CONCLUSION

Top down micro-patterning technique using micro-mechanical bending (M2B) method for control over the structure of CVD grown of CNTs forest has been investigated. A detailed characterization of process parameters was carried out to investigate the effect of reflection from various parameters on M2B technique. Subsequently, the features of the resultant surface have been analysed. Potential application of processed CNTs after the M2B method with the likes of monolithically integrated reflector-absorber array or encoder, angle sensor, strain sensor and micro concave mirror have been explored.

6.0 ACKNOWLEDGEMENT

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