Carbon nanotubes based flexible temperature sensors

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This paper presents the design, fabrication and investigation of carbon nanotubes (CNTs) based flexible Al/CNT/Al temperature sensor. The sensor has been fabricated by the deposition of CNTs on the adhesive elastic polymer tape and packing it in the elastic casing. The diameter of multiwall nanotubes (MWNTs) was in the range of 10-30 *nm*. The nominal thickness of the CNTs layers in the samples was ~ 300-430 μm. The inter-electrodes distance (length) and width of the surface-type samples were in the range of 4-6 mm and 3-4 mm respectively. The investigations showed that DC resistance of the sensor decreases in average by 1.4 times as the temperature increases from 20 $^\circ$C to 70 $^\circ$C. The resistance-temperature relationship shows wide range sensitivity, and the simulation is in good agreement with the experimental results.

1. Introduction

Temperature sensors are widely used in industry, in particular, aerospace, nuclear, mechanical, chemical and medical technologies. Since their discovery in 1991 carbon nanotubes (CNTs) are intensively investigated [1]. CNTs are interesting due to their unique electronic and mechanical properties. Electronically, CNTs can be metallic, semiconducting, or small-gap semiconducting (SGS), depending on the orientation of the graphene lattice with respect to the axis of the tube [2]. Different types of sensors on the base of single-wall carbon nanotubes (SWNTs) [3-6], double-walled carbon nanotubes (DWNTs) [7] and multi-walled carbon nanotubes (MWNTs) [8] have fabricated and investigated.

The temperature and chemical sensitivity of carbon nanofilms made on diamond surface by high temperature surface modification followed by plasma treatment were also investigated [9]. The structure of nanofilms was found amorphous. The films electrical conductance was sensitive to temperature and exposure to vapors of different organic compounds. In another study highly disordered multiwalled carbon nanotubes of large outer diameter (60 nm) were fabricated by means of a chemical vapor deposition process and their temperature dependent electrical transport was investigated [10].

So called flexible electronic sensors [11-15], in particular, flexible temperature sensors, which improve greatly the functionality of integrated bio-parameter monitoring systems becoming more interesting for the researchers, especially for body temperature controlling systems. The miniaturized flexible temperature sensors based on polymer compositions filled with multiwalled carbon nanotubes were described [16]. This sensor didn't show tensometric effect that was very common for other carbon-polymer sensors. The temperature sensitivity of the sensor was around of 0.13%/K. Based on an array of carbon nanowires temperature sensor that was written by a 30 KeV Ga$^+$ focused ion beam on diamond substrate has been developed [17]. In the temperature range from 40 to 140 $^\circ$C the sensor shows an exponential increase of current with temperature at a rate of 0.1dB/$^\circ$C. Low-temperature resistance sensor based on CNTs grown on nickel film using ion beam deposition technique for measurement at 10 K-300 K was developed [18]. It was found that CNTs behave as semiconductors.

In continuation of our efforts for the fabrication of various types of sensors [19, 20], we designed, fabricated and investigated the carbon nanotubes based flexible temperature sensors.

2. Experimental procedure

Commercially produced (Sun Nanotech Co Ltd., China) CNTs powder was deposited on the adhesive elastic polymer tape of thickness of 35 μm, with built-in Al foil electrodes, and then it was covered by the same kind of tape. As shown in figure 1 the tape played a role of elastic casing. The diameter of multiwalled nanotubes (MWNTs) was in the range of 10-30 *nm*. The nominal thickness of the CNTs layers was ~ 300-430 μm. The inter-electrodes distance (length between electrodes) and widths of the surface-type samples layers were in the range of 4-6 mm and 3-4 mm respectively. DC resistance of the samples was measured by using ESCORT ELC-132

A meter. Laboratory setup for the measurement of the influence of temperature to the resistance of the samples was used for the experiments. The experimental error in the measurement of the temperature was $\pm 1^\circ$C.
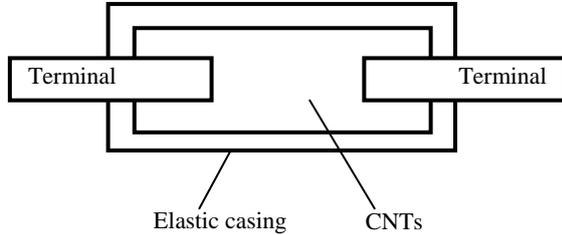
Fig.1. Al/CNT/Al resistance temperature sensor.

3. Results and discussion

Fig. 2 shows resistance-temperature relationship for one of the Al/CNT/Al sensors. The DC resistance of the sensors was decreased in average by 1.4 times respectively with the increase in temperature from 20 $^\circ$C to 70 $^\circ$C. The effects of temperature to the sensors' resistances were approximately same for the thicker CNT films (~430 μm) and thinner films (~300 μm).

The resistance temperature coefficient (S) of the sample can be calculated by:

$$S = \Delta R / (R_o \Delta T) \qquad (1)$$

where R_o, ΔR and ΔT are initial value of the sensor's resistance, change in the resistance and temperature respectively. From data presented in figure 2 it can be found that at 20 $^\circ$C the value of S is -1.26% $^\circ$C^{-1}. The temperature sensitivity of the investigated Al/CNT/Al sensor was found larger than that of hydrogenated multiwalled carbon nanotubes (S = - 0.16% $^\circ$C^{-1}) [10], carbon nanofilms deposited on diamond crystals (S = -0.14% $^\circ$C^{-1}) [9] and carbon-polymer flexible temperature sensor (S= -0.13% K^{-1}) [16].
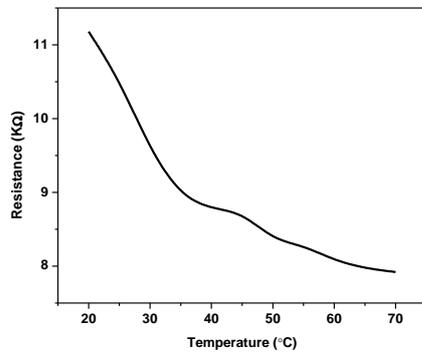
Fig.2. Resistance-temperature relationship of the one of Al/CNT/Al sensors.

The sensor's resistance (R) is determined as [21]:

$$R = \frac{d\rho}{A} = \frac{d}{\sigma A} \qquad (2)$$

where d is the length or inter-electrode distance and A is the cross-section of the CNT layer, and ρ is the resistivity ($\rho = \dfrac{1}{\sigma}$, where σ is conductivity) of the CNT layer. As CNT is a nanopowder, for the observed resistance-temperature relationship the increase in the conductivity of the CNT film under the effect of temperature may be due to the increase in concentration of charge carriers, same like in semiconductors [22]. Using an exponential function given in equation (3), the relationship can be represented as given in equation (4) [23]:

$$f(x) = e^{-x} \qquad (3)$$

$$R/R_o = e^{-\Delta T \,(Tm/T)K} \qquad (4)$$

where R is the sample's resistance at elevated temperatures (T) , T_m is maximum temperature, K is resistance temperature factor. From the experimental data shown in Fig. 2, the calculated average value of K is 0.689 10^{-2} $^\circ$C^{-1}.

Experimental and simulated (by using equation (4)) results are plotted in Fig. 3 and can be observed in good agreement.
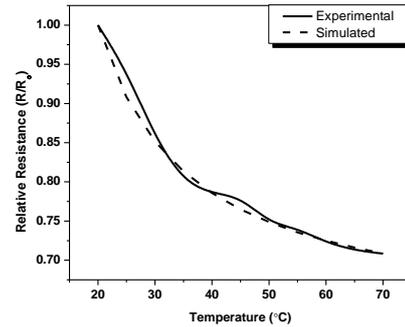
Fig. 3. Experimental (solid line) and simulated (dashed line) relative resistance-temperature relationships of the Al/CNT/Al sensors (R_o and R are initial resistance and resistance at elevated temperatures respectively).

The mechanism of conductivity in CNT samples can be considered as transitions between spatially separated sites, or particles that can be attributed to the Percolation Theory [24, 25]. According to Percolation Theory, the effective conductivity (σ) of the CNT samples can be calculated as;

$$\sigma = \frac{1}{LZ} \qquad (5)$$

where L is a characteristic length, depending on the concentration of the sites, Z is the resistance of the path with the lowest average resistance. With an increase of temperature, the CNT layer will be heated that will cause the reduction of Z due to generation of charge carriers. On the other hand, as the CNT nano-particles are encapsulated, due to the thermal expansion the particles will be squeezed and the contact areas between particles or effective cross-section of the sample (equation 2) will be increased as well that will decrease the resistance of the

sample As a result, the conductivity of the CNT samples increases and the resistance decreases with increase of temperature accordingly, as is observed experimentally (Fig. 2). The CNT system can be assumed as a bulk hetero system that results to high sensitivity of the CNT layers to the effect of temperature. With the rise in temperature the increase in inter-particles contact areas and intrinsic conductivity of the nanoparticles takes place that results in an increase of the conductivity and decrease of the resistance of the samples accordingly.

Formally, the structure of the investigated sensors is the same as presented in [26], as in both cases the flexible substrates are used for deposition of the CNT layer. But in [26] the flexible substrate was fixed on silicon wafer by gluing. Moreover in our case the CNT layer is actually encapsulated in plastic casing to prevent effect of humidity to the resistance as CNT based layers are very sensitive to the influence of humidity [3-8], i.e. in this case the influence of the humidity to electric properties of the sensors is neglected.

As the experimental resistance-temperature (Fig. 2) relationship for the Al/CNT/Al sensor is quasi-exponential, it may be easy to linearize it by nonlinear op-amps [27].

4. Conclusions

The surface-type Al/CNT/Al flexible temperature sensors were designed, fabricated and investigated. Resistance of the sensors decreases as the temperature increases, i.e. resistance-temperature relationship has semiconductive behavior. The average temperature sensitivity of the samples is -1.26% $^{\circ}C^{-1}$. The resistance-temperature relationship of the sensor was simulated. For the explanation of a conduction mechanism, the percolation theory is used. The CNT system is assumed as a bulk hetero system that results to a high sensitivity of the CNT layers to the effect of temperature. In this system the increase in the inter-particle contact areas and intrinsic conductivity of the nanoparticles takes place as well, which results in increase of the conductivity and decrease of the resistance of the samples with increase of the temperature accordingly. The temperature sensors show good performance, and as the CNT layer is encapsulated in flexible elastic casing the effect of humidity to the electric properties of the sensors is neglected.

Acknowledgements

References

[1] S. Iijima, Nature **354**, 56 (1991).
[2] R. J. Grow, Q. Wang, J. Cao, D. Wang, H. Dai, Appl. Phy. Lett. **86**, 093104 (2005).
[3] M. Saleem, Kh. S. Karimov, Z. M. Karieva, A. Mateen, Physica E **43**, 28 (2010).
[4] C. Cantalini, L. Valentini, I. Armentano, L. Lozzi, J. M. Kenny, S. Santucci, Sens. Actuators B **95**, 195 (2003).
[5] P. S. Na, H. Kim, H. M. So, K. J. Kong, H. Chang, B. H. Ryu, Y. Choi, J. O. Lee, B. K. Kim, J. J. Kim, J. Kim, Appl. Phy. Lett. **87**, 093101 (2005).
[6] M. Rinkio, M. Y. Zavodchikova, P. Torma, A. Johansson, Phys. Stat. Sol. (b) **245-10**, 2315 (2008).
[7] D. Tang, L. Ci, W. Zhou, S. Xie, Carbon **44**, 2155 (2006).
[8] K. Varghese, P. D. Kichambre, D. Gong, K. G. Ong, E. C. Dickey, C. A. Grimes, Sens. Actuators B **81**, 32 (2001).
[9] V. Kumar, A. A. Bergman, A. A. Gorokhovsky, A. M. Zaitsev, Carbon **49**, 1385 (2011).
[10] A. L. Friedman, H. Chun, D. Heiman, Y. J. Jung, L. Menon, Physica B **406**, 841 (2011).
[11] M. Billinghurst, T. Starner, IEEE Computer **32**, 57 (1999).
[12] R. F. Service, Science **301**, 909 (2003).
[13] S. Park, S. Jayaraman, Eng. Med. Bio. Magz. IEEE **22**, 41 (2003).
[14] R. Paradiso, A. Gemignani, E. P. Scilingo, D. D Rossi, Proc. of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Cancun, Mexico, 3720 (2003).
[15] D. D. Rossi, F. Lorussi, A. Mazzoldi, P. Orsini, E. P. Scilingo, Sensors and sensing in biology and engineering, Springer Wien, 379 (2003).
[16] M. Sibinski, M. Jakubowska, M. Sloma, Sensors **10**, 7934 (2010).
[17] A. M. Zaitsev, A. M. Levine, S. H. Zaidi, Phys. Stat. Sol. (a) **204-10**, 3574 (2007).
[18] A. Saraiya, D. Porwal, A. N. Bajpai, N. K. Tripathi, K. Ram, Metal-Organic and Nano-Metal Chemistry **36**, 163 (2006).
[19] M.T. Saeed, F. A. Khalid, Kh. S. Karimov, M. Shah, Optoelectron. Adv. Mater.-Rapid Commun. **4**(6), 888 (2010).
[20] Kh. S. Karimov, M. T. Saeed, F. A. Khalid, S. A. Moiz, Chinese Physics B 20-4, 040601(2011).
[21] M. A. Omar, Elementary Solid State Physics: Principles and Applications, Pearson Education Inc., Singapore 1999.
[22] D. A. Neamen, Semiconductor Physics and Devices: Basic Principles, Richard D Irwin Inc., Boston, 1992.
[23] A. Croft, R. Davison, M. Hargreaves, Engineering Mathematics: A Modern Foundation for Electronic, Electrical and Control Engineers, Addison-Wesley Publishing Company, Great Britain 1993.
[24] C. J. Brabec, V. Dyakonov, J. Parisi, N. S. Sariciftci, Organic Photovoltaics: Concepts and Realization, Springer-Verlag, Berlin Heidelberg, 2003.
[25] H. Bottger, V. V. Bryksin, Hopping Conductions in Solids, VCH Publishers, Akademie-Verlag, Berlin, 1985.
[26] L. Yong, W. Wanlu, L. Kejun, H. Chenguo, H. Zhi F. Qing, Chinese Science Bulletin **48-2**, 125 (2003).
[27] R. G. Irvine, Operational Amplifiers Characteristics and Applications, Prentice Hall, New Jersey, 1994.

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