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Strain Sensor Based on the Biological Nanomaterial

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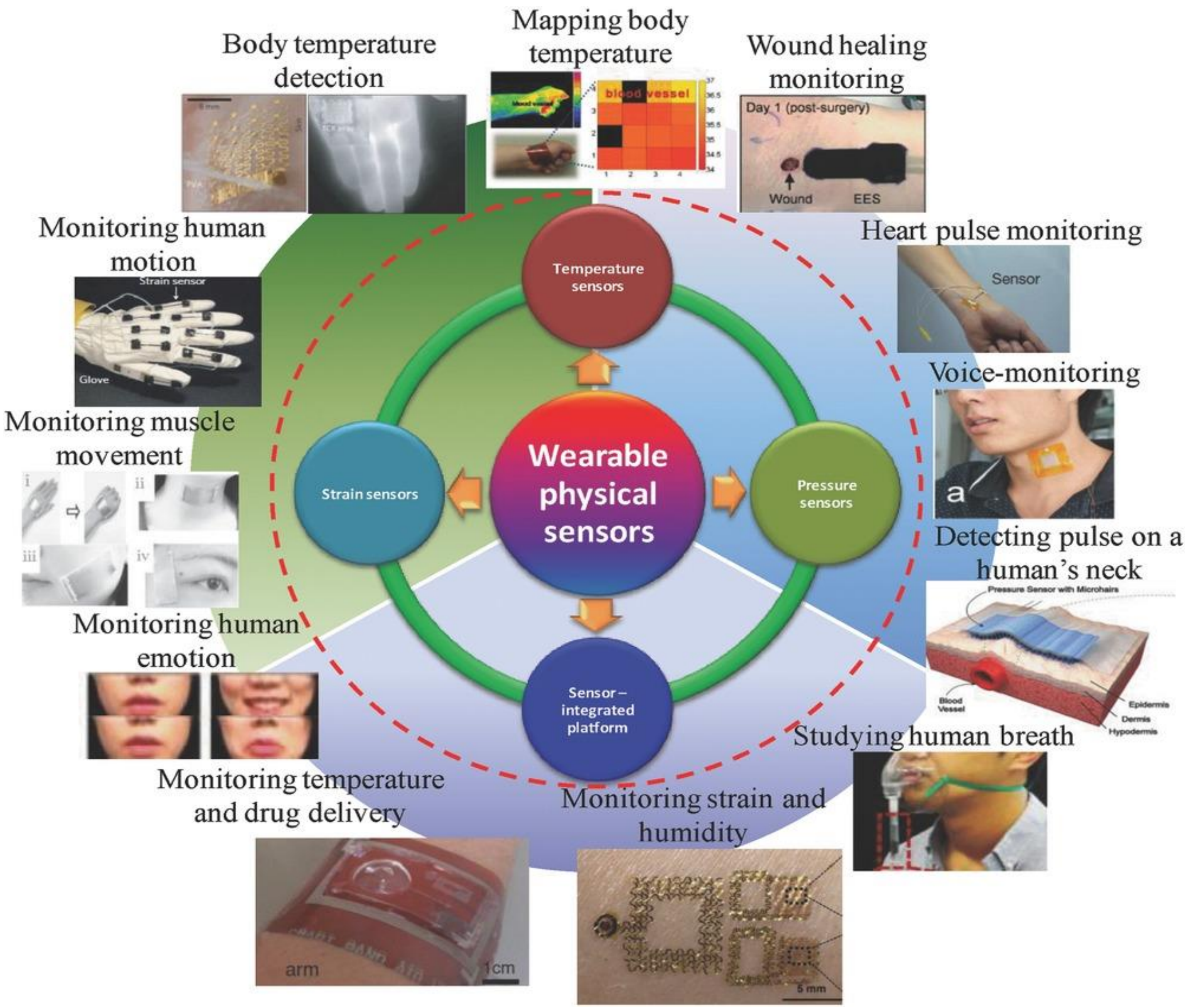
Applications of strain sensors in medicine



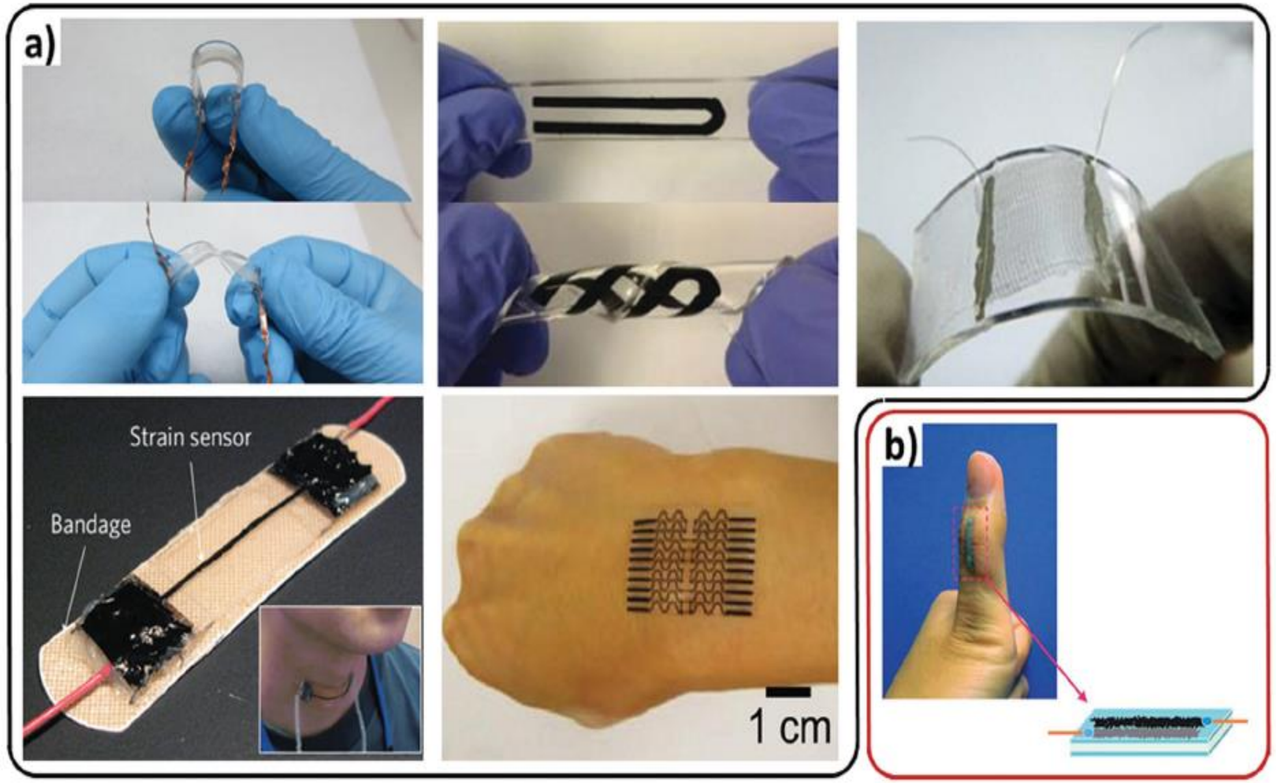
The sensors are widely used as wearable devices for monitoring human activity and health monitoring, for example:

- ✓ Body temperature detection and body temperature mapping.
- ✓ Monitoring wound healing.
- ✓ Heart rate monitoring.
- ✓ Voice monitoring.
- ✓ Study of human breathing.
- ✓ Monitoring of human movements.
- ✓ Muscle movement monitoring.
- ✓ Monitoring of human emotions.
- ✓ Integrated sensor platform: monitoring temperature and drug delivery.
- ✓ Body moisture control.

Trung T. Q., Lee N. E. Flexible and stretchable physical sensor integrated platforms for wearable human-activity monitoringand personal healthcare //Advanced materials. – 2016. – V. 28. – №. 22. – P. 4338-4372.

Materials for creating strain sensors

One of the important challenges is the selection of suitable materials and methods for the manufacture of flexible strain gauges for monitoring biological objectives. The fabrication process for flexible sensors must be inexpensive and scalable, capable of large-scale production, and have acceptable degrees of biocompatibility. To date, strain gauges have been fabricated using low-dimensional carbons (eg, carbon black, carbon nanotubes, and graphene), nanowires, nanoparticles, and their hybrid micro / nanostructures. Silicone-based elastomers (eg polydimethylsiloxane, Ecoflex and Dragon Skin) and rubbers (eg natural rubber and thermoplastic elastomers) are the most commonly used polymers as matrices for flexible materials using in soft load cells.

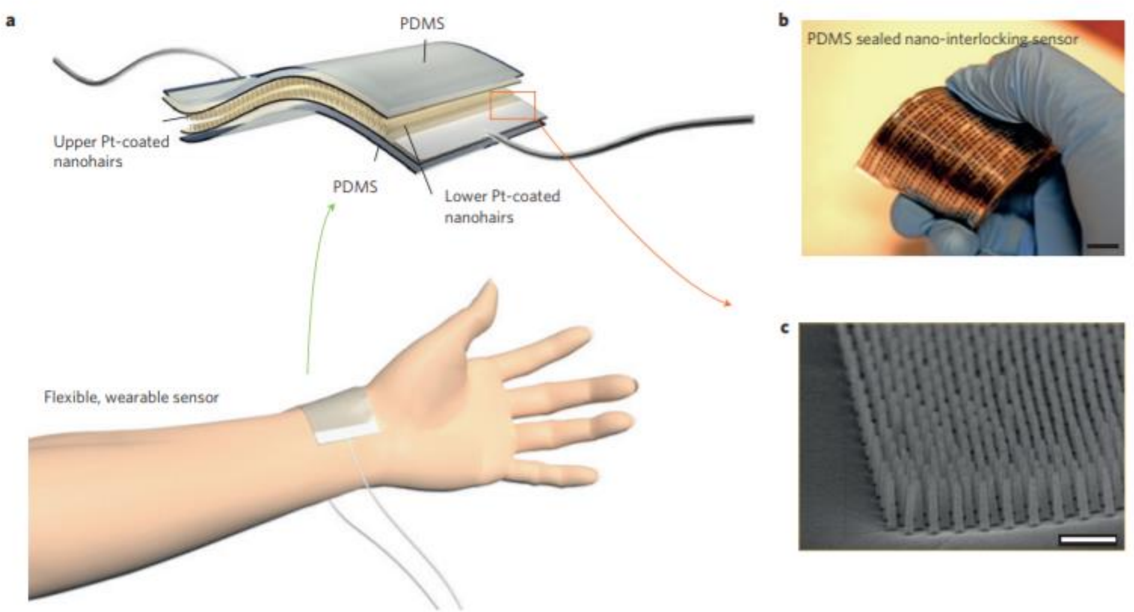


Various flexible, skin-mounted and wearable strain gauges
made of functional composites: nanomaterials and polymers, where:
a) resistive-type sensors, b) capacitive-type sensors

- ✓ Strain sensors convert mechanical deformations into electrical signals.
- ✓ There are several other types of strain gauges based on various physical phenomena, for example: fiber Bragg grating, Raman shift, liquid metals, piezoelectricity [1].
- ✓ However, the practical implementation of these strain gauges for skin mount and wearable applications remains challenging, mainly due to sophisticated measurement equipment, low resolution and poor dynamic performance.
- ✓ Resistive and capacitive strain gauges are more suitable for medical applications.
- ✓ Resistive strain gauges are characterized by a special ease of maintenance and processing of a useful signal, with deformation of which its resistance changes [2].

1. *N. Hu , T. Itoi , T. Akagi , T. Kojima , J. Xue , C. Yan , S. Atobe , H. Fukunaga , W. Yuan , H. Ning , Carbon 2013 , 51 , 202*
2. *M. Amjadi , A. Pichitpajongkit , S. Lee , S. Ryu , I. Park , ACS Nano 2014 , 8 , 5154 .*

Layers without carbon nanotubes (metal coated)

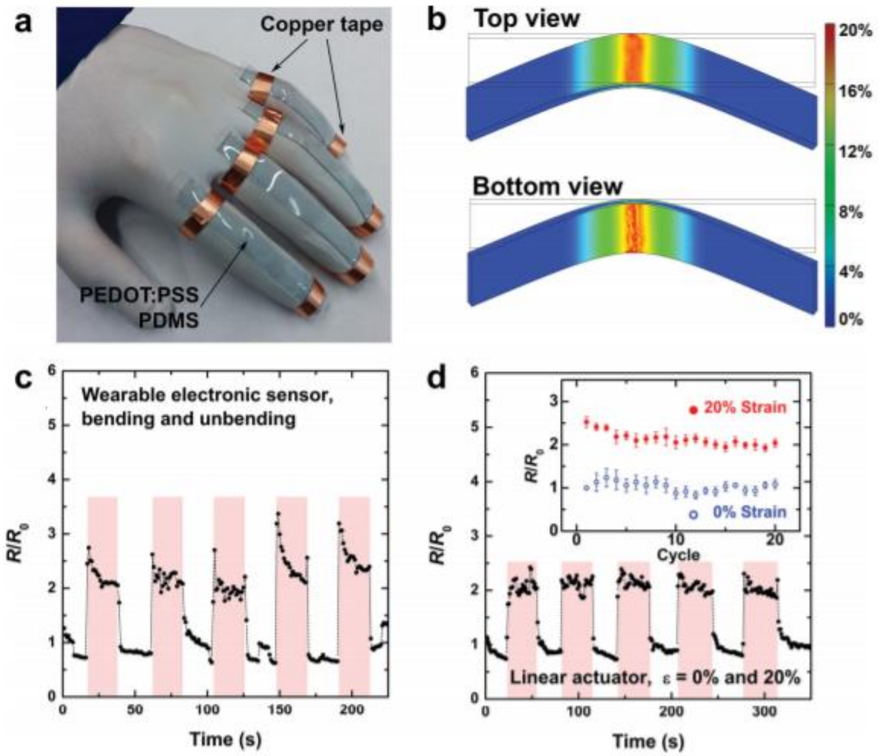


Multiplex, flexible strain-gauge sensor based on the reversible interlocking of Pt-coated polymer nanofibers:

(a) Schematic of the assembly and operation of a flexible sensor layer sandwiched between thin PDMS supports (500 μm thickness each).

(b) Photo showing the flexibility. (c) SEM image , scale bar 1 μm [1]

1. P. Changhyun, G. Y. Lee, T. I. Kim, S. M. Kim, H. N. Kim, S. H. Ahn, K. Y. Suh // Nature materials, 11 (9) (2012) 795.
2. S. Savagatrup, E. Chan, S. M. Renteria-Garcia, A. D. Printz, A. V. Zaretski // Advanced Functional Materials, 25 (3) (2015) 427-436.



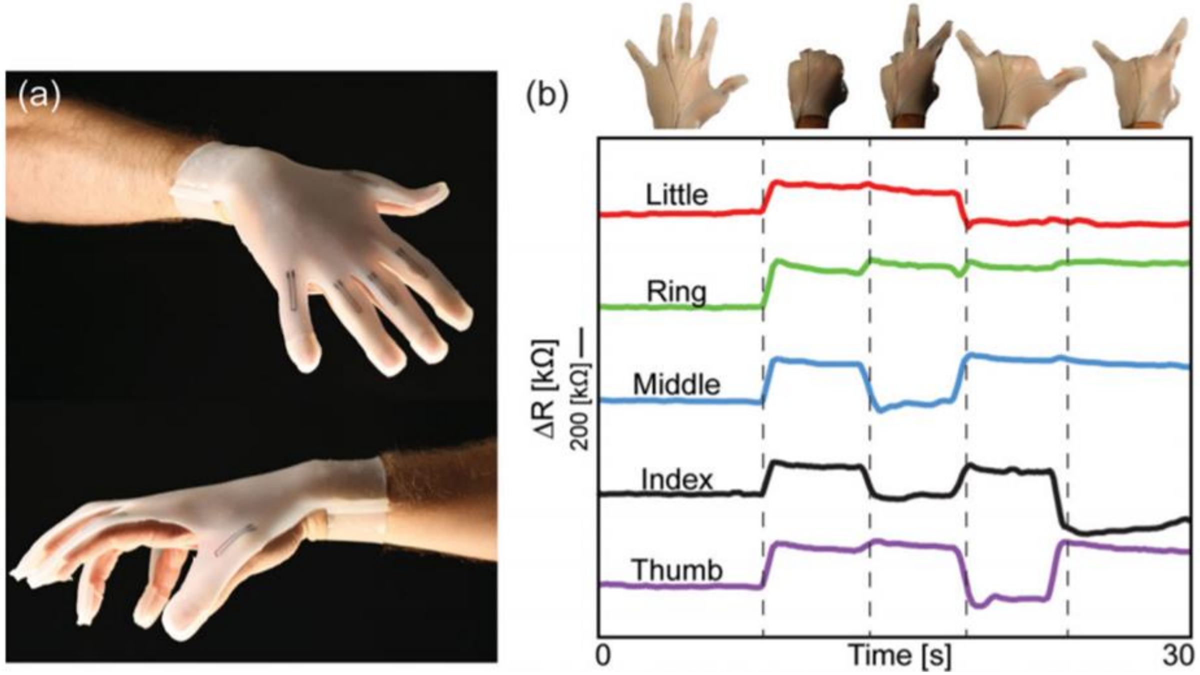
a) Photograph of the devices comprising PEDOT: PSS films with 5% DMSO and 10% Zonyl transferred onto thin PDMS substrates (1 mm thick) and adhered to a nitrile glove using conductive copper tape.

b) Computational analysis of strain produced in the thin films with the radius curvature of 5 mm.

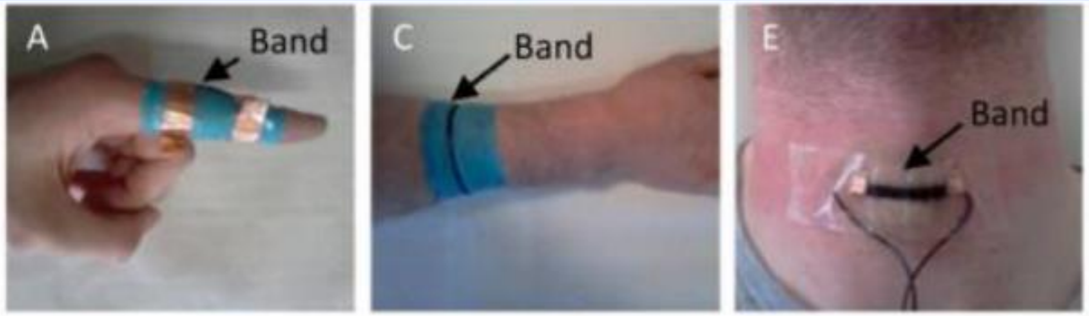
c) Plot of relative resistance (R/R_0) as a function of time for the devices placed on the human hand.

d) R/R_0 vs time of the devices on the linear actuator cycling between 0% and 20% strains [2].

Sensors containing carbon nanotubes

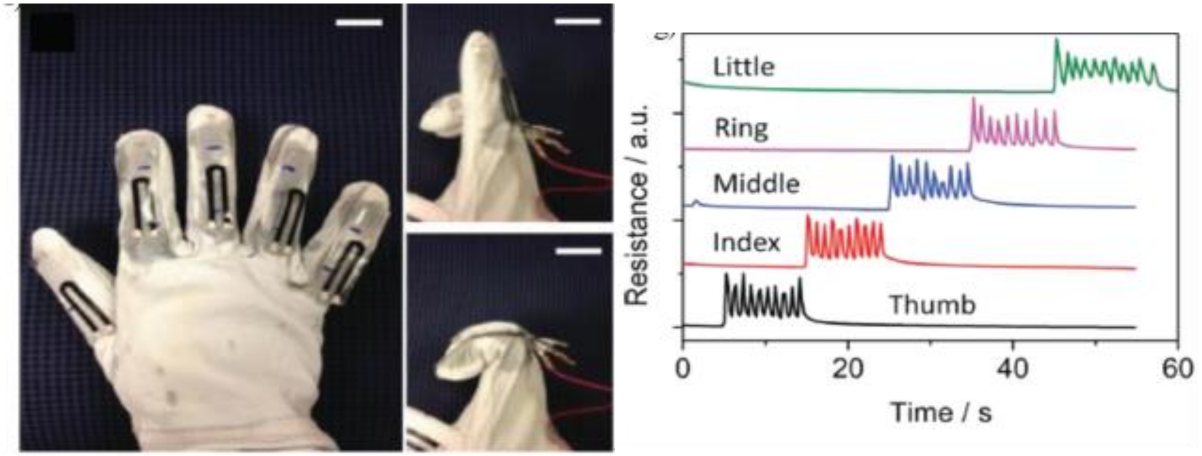


Deformation sensor based on resistive ink from carbon in elastomer [1]



Graphene-infiltrated elastic bands [2]

- ✓ When using nanomaterials containing carbon nanoparticles (nanotubes, graphene), there is a very high potential for obtaining a record tensosensitivity.
- ✓ Structures made of carbon nanotubes under the influence of deformation (tension, compression, bending) can significantly change their electrical conductivity in comparison with a metal or oxide nanowire.
- ✓ At the same time, structures made of carbon nanotubes have high strength and resistance to cyclic mechanical stress.



Photographs of gloves with five sensors made of graphene oxide and nanocellulose, changes in the resistance of five independent strain sensors [3]

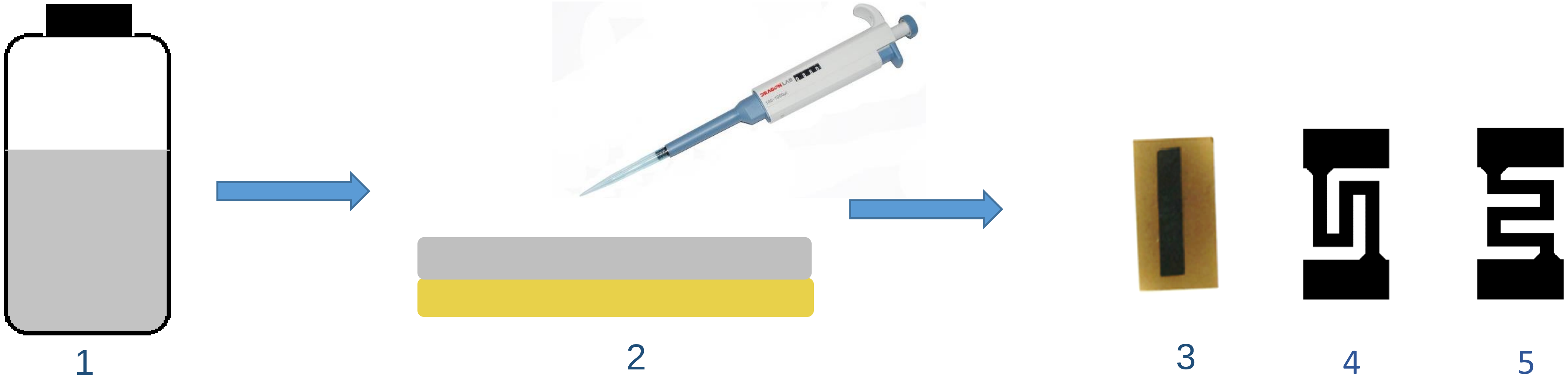
1. *J. T. Muth, D. M. Vogt, R. L. Truby, Y., Mengüç, D. B. Kolesky, R. J. Wood, J. A. Lewis // Advanced Materials, 26(36) (2014) 6202-6202.*
2. *C. S. Boland, U. Khan, C. Backes, A. O'Neill, J. McCauley, S. Duane // ACS nano, 8(9) (2014) 8819-8830.*
3. *Trung T. Q., Lee N. E. // Advanced materials. – 2016. – V. 28. – №. 22. – P. 4338-4372.*

Characteristics of some sensors according to the review [1]:

Active materials	Sensitive mechanism	Bending / Stretching, (%)	Coefficient of strain-sensore, *S*
Single wire ZnO	Piezoelectric	Bending (1.2)	1250
Nanowirewire matrix ZnO		Bending (0.8)	1813
Single nanowire $ZnSnO_3$		Bending (0.32)	3740
Hybrid SWCNTs	Tenzoresistive	Stretching (100)	62
Rubber/MSWT/rubber		Stretching (620)	43
MSWNT/composite polyurethane		Stretching (400)	69
CNT/polydimethylsiloxane/CNT	Capacitive	Stretching (300)	0.97
SWCNT/Silicone/SWCNT		Stretching (100)	0.99
SWCNT/ecoflex/SWCNT		Stretching (50)	0.969

1. M. Amjadi, K-U. Kyung, I. Park, and M.Sitti // Advanced Functional Materials, 26 (2014) 1678-1698.

Sensor preparation containing biological material and carbon nanotubes

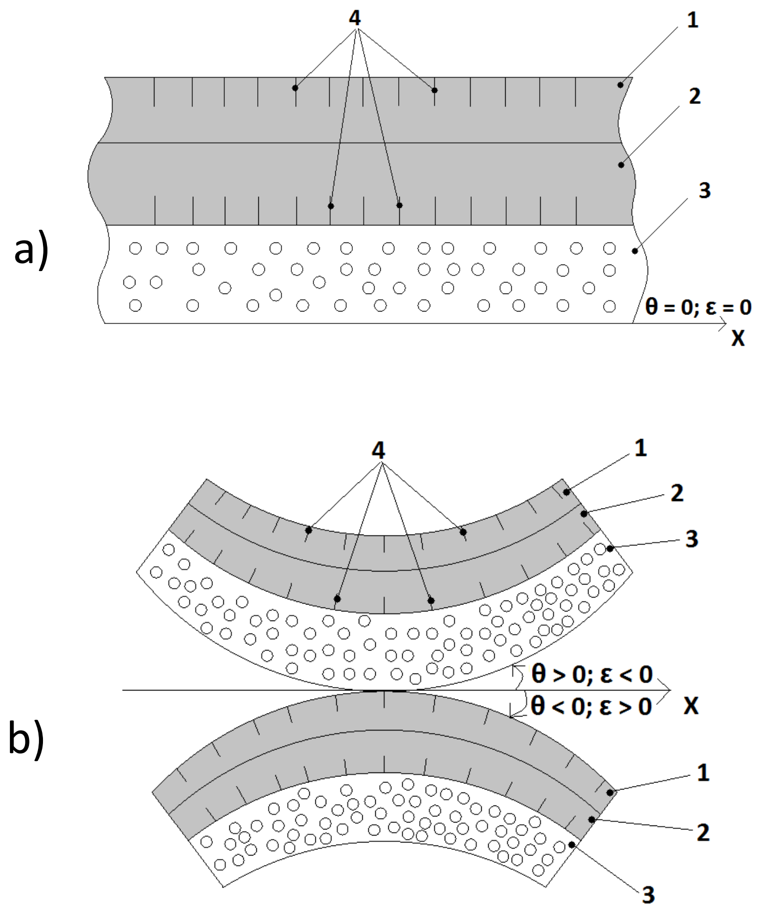


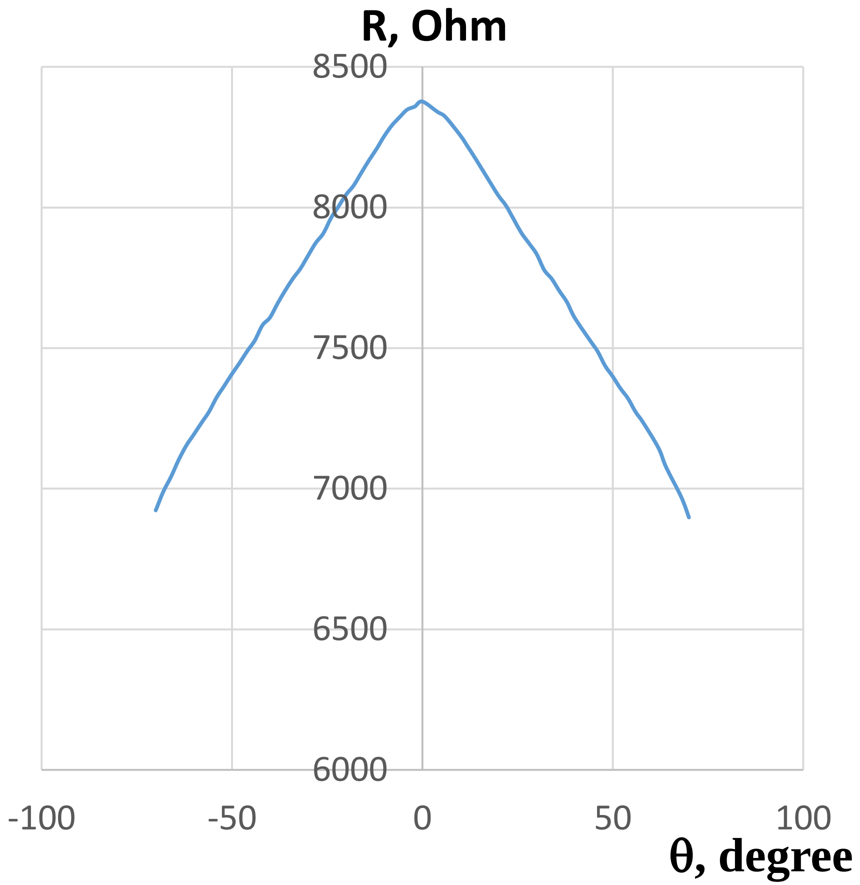
Some preparation steps:

- The aqueous dispersion containing multi-walled carbon nanotubes (MWCNTs) was carefully moved and dispersed.
- Bovine serum albumin (BSA) was added to the aqueous dispersion in the composition of MWCNTs, and the resulting BSA/MWCNTs dispersion was carefully moved.
- The components of the BSA/MWCNTs aqueous dispersion had a ratio of 25% wt.BSA/0.3% wt.MWCNTs.
- The BSA/MWCNTs dispersion was applied on polyethylene or chintz substrates with a thickness of 50-100 μm by silk-screen.
- The layers were dried printing or airbrushing under the action of laser radiation (~ 970 nm, power 0.3 W/cm^2).
- The layers were in the form of a strip or a meander. Strip: (15 ÷20) mm x (8 ÷10) mm x (0.5 ÷1.5) μm. Meander: width - 1.5 mm, length - 20 mm, banks - 10x4.5 mm.
- The shape of the layers, i.e. sensor (see figure, 3,4,5) was imparted under the action of laser radiation: power - 1.2 W/cm^2, laser beam spot - 35 μm.

BSA/MWCNTs nanomaterial strain sensor (thick film)

$$R = R_0\{1 - (\alpha\theta)^2\}. \qquad (1)$$





Typical dependence $R(\theta)$ for sensor of nanomaterial BSA/MWCNTs nanomaterial, thickness 10.5 μm. $S_\theta \sim 0.25$ % /degree

1. *L.P. Ichkitidze, et al. UNIPOLAR DEFORMATION SENSOR. Patent RU No. 2 685 570.*

Some parameters of strain sensors made of nanomaterial films containing BSA and MWCNTs

$\Delta l = l - l_0$;

$\varepsilon = \Delta l / l_0$;

$S = (\Delta R / R_0)/\varepsilon$

$S_\theta = (\Delta R / R_0)/\Delta\theta$;

Nanomaterial	d, μm	ρ, mOhm·m	S_θ,	S
BSA/MWCNTs	~ 0.5	~ 60	~ $2\cdot10^{-3}$ (1/degree) ~0.2 (%/degree)	~ 40
	~ 0.2	~ 80	~ $5\cdot10^{-3}$ (1/degree) ~0.5 (%/degree)	~ 100
	~ 0.4	~ 20	~ $13\cdot10^{-3}$ (1/degree) ~1.3 (%/degree)	~ 150
	~ 0.1	~ 40	~ $17\cdot10^{-3}$ (1/degree) ~1.7 (%/degree)	~ 160

* Note: bending range $\Delta\theta$ = +/– 150 degree.

Conclusion

- Films of composite nanomaterial (BSA / MWCNT) in the composition of bovine serum albumin (matrix) and multi-walled carbon nanotubes (filler) were studied as a prototype of a bending strain sensor.
- The films were obtained by applying an aqueous dispersion of a BSA / MWCNT composite nanomaterial (25 wt% BSA / 0.3 wt% MWCNT) on polyethylene or textile (calico) substrates. Laser irradiation of the BSA / MWCNT film changed its resistivity and its parameters, which are characteristic of the prototype strain sensor.
- The thickness of the films was varied in the range $d \sim 0.2–20$ μm.
- Thin films ($d < 1$ μm) exhibited the properties of a bipolar strain sensor, i.e. when bending in the form of a concavity, the resistance decreases, and when bending in the form of a curvature, the resistance increases with an increase in the bending angle θ. Thick films ($d > 1$ μm) exhibited the properties of a unipolar strain sensor, i.e. for any kind of bending (concavity or curvature), the resistance decreases with increasing bending angle θ.
- Acceptable strain-resistance sensitivities are realized for all films in a wide range of bending angle $\Delta\theta$ = +/- 150 degree. The highest sensitivity of the change in the relative resistance from the bending angle is $S_\theta \sim 2\%$ / degree.
- Films of the BSA / MWCNT composite nanomaterial contain a small amount of carbon nanotubes, have a high degree of biocompatibility, and can be applied directly to the human skin surface. They can serve as bending strain sensors.
- The proposed strain sensors will make it possible to monitor the state of human health and diagnose its various diseases, for example: movements of the limbs, phalanges, breathing, tumors, stroke, etc.

Thank you for your attention!

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