nature portfolio

https://doi.org/10.1038/s41596-020-00489-8

Supplementary information

Fabrication, characterization and applications of graphene electronic tattoos

In the format provided by the authors and unedited

Supplementary Table 1. Comparative performance, fabrication scale, advantages and drawbacks of different electronic tattoos and epidermal sensors. Color code: green – good, yellow – acceptable, red – needs improvements.

	Graphene Electronic Tattoos (This work)	**PEDOT:PSS tattoos** [1-2]	**On-body inks** [3]	**Gold tattoos** [4]	**Gold microcrack tattoos** [5]	**Unsupported gold tattoos** [6]	**Epidermal sensors** [7]	**Ag/AgCl medical grade gel electrodes**
Fabrication	Cheap, low-cost, scalable, low-end tools used	cheap, scalable, low-end tools	cheap, scalable, requires advanced chemistry	Cheap, low-cost, scalable, low-end tools used	Complicated cleanroom based technology	Cheap, low-cost, scalable	Cleanroom, microfabrication	Market ready technology
Stand-alone or require support	stand alone	requires support	requires support	requires support	stand alone	stand alone	Stand alone	Self-adhesive
Stretchability	superior, 40% stretchability	good	good, up to 20% stretchability	Superior, >45% stretchability	good, up to 20% stretchability	Superior, up to 40% stretchability	mixed	bad
Adhesion to skin	Superior, self-adhesive	good, but uses glue	good, but still uses acrylyc tape for better adhesion	moderate, requires adhesive spray	Superior	Superior	moderate-poor, depending on overall thickness	Superior (due to adhesive)
Transparency	yes, >85%	semi-transparent	no	no	no	semi-transparency	depending on the constitution	no
Impedance to Skin (@10 kHz)	6-10 kOhm	~5kOhm	>30 kOhm*	5-10 kOhm	N/A	3-4kOhm	N/A	1-2 kOhm
Rs	300-1000 Ohm/sq	50-500 Ohm/sq	1-10 Ohm/sq	N/A	N/A	N/A	N/A	non conductive laterally
Harmful solvents (in direct contact with skin)	no	no	yes	N/A	N/A	no	No	N/A
Stability (storage)	Superior, >1year storage (ambient)	Great	Great (>1 month)	Great	N/A	N/A	Superior, packaged device	<1 week when exposed to ambient
Thickness of active part	1 nm	240-360 nm	1 - 20 um	110 nm	100-400 nm	70-100 nm	~mm	1-2 mm
Thickness of supporting part	200 nm	1.5 um	N/A	1.4 um	no	no	~mm	1-2 mm
Associated costs, including equipment	0.5$/cm2 for graphene supply. Only low cost equipment	Low. Highest-end equipment is inkjet printer	Low. Mostly chemicals and chemistry associated costs.	Low. Mostly chemicals and chemistry associated costs.	high, cleanroom-related equipment costs	N/A	High, electronic devices, fabrication, packaging	N/A
Skin Irritation	no	no	no	no	N/A	no	No, even after 1 week	possible after long wear

Supplementary Table 2. Comparative graphene prices table, status at October 2020.

Supplier	Region	Price, $/cm2	Link
Grolltex	North America	0.95	https://grolltex.com/product/monolayer-graphene-on-copper-foil-6-x-6-150-mm-x-150-mm/
ACS Materials	North America	3.23	https://www.acsmaterial.com/graphene-on-copper-foil.html
Graphene Supermarket	North America	4.36	https://graphene-supermarket.com/Single-Layer-Graphene-on-Copper-foil-4-x4-CVD-Cu.html
2D Semiconductors	North America	12.01	https://www.2dsemiconductors.com/graphene-on-cu-foils/
Graphenea	Europe	7.17	https://www.graphenea.com/collections/buy-graphene-films/products/monolayer-graphene-on-cu-4-inches?variant=51671644051
cqmxi.com	Asia	0.53	http://www.cqmxi.com/product/detail-80.html

References

1. Ferrari, L. M., Ismailov, U., Badier, J.-M., Greco, F. & Ismailova, E. Conducting polymer tattoo electrodes in clinical electro- and magneto-encephalography. *npj Flex. Electron.* **4**, 1–9 (2020).
2. Ferrari, L. M. *et al.* Ultraconformable Temporary Tattoo Electrodes for Electrophysiology. *Adv. Sci.* **5**, 1700771 (2018).
3. Ershad, F. *et al.* Ultra-conformal drawn-on-skin electronics for multifunctional motion artifact-free sensing and point-of-care treatment. *Nat. Commun.* **11**, 3823 (2020).
4. Wang, Y. *et al.* Low-cost, µm-thick, tape-free electronic tattoo sensors with minimized motion and sweat artifacts. *npj Flex. Electron.* **2**, 6 (2018).
5. Gong, S. *et al.* Local Crack-Programmed Gold Nanowire Electronic Skin Tattoos for In-Plane Multisensor Integration. *Adv. Mater.* **31**, 1–8 (2019).
6. Miyamoto, A. *et al.* Inflammation-free, gas-permeable, lightweight, stretchable on-skin electronics with nanomeshes. *Nat. Nanotechnol.* **12**, 907–913 (2017).
7. Krishnan, S. R. *et al.* Wireless, Battery-Free Epidermal Electronics for Continuous, Quantitative, Multimodal Thermal Characterization of Skin. *Small* **14**, 1803192 (2018).