

EE 396V – Homework #3

All papers from 2017-2019 that use graphene as electronic tattoos:

1. Ameri, S. K.; Ho R.; Jang, H.; Tao, L.; Wang, Y.; Wang, L.; Schnyer, D. M.; Akinwande, D.; Lu, N. "Graphene Electronic Tattoo Sensors" ACS Nano, vol. 11, no. 8, July 18, 2017. [Online]. Available: <https://pubs.acs.org/doi/10.1021/acsnano.7b02182>. [Accessed Oct. 28, 2019]
 - a. This work shows the development of a stretchable and transparent graphene based electronic tattoo (GET) sensor that is only sub-micrometer thick but demonstrates high electrical and mechanical performance. It also explains how a GET can be fabricated through a simple "wet transfer, dry patterning" process directly on tattoo paper, allowing it to be transferred on human skin exactly like a temporary tattoo, except this sensor is transparent. Because of the open-mesh design of the filamentary serpentine, the GET is breathable and has negligible mechanical stiffness – so it is almost imperceptible both mechanically and optically. GET has been used for various physiological measurements including electrocardiogram (ECG), electromyogram (EMG), electroencephalogram (EEG), skin temperature, and skin hydration, each of which has been validated by a corresponding gold standard sensors. As dry electrodes, the GET–skin interface impedance is almost as low as that of Ag/AgCl gel electrodes, which can be attributed to its ultimate conformability. As a result, the GET has achieved comparable SNR with gel electrodes and also demonstrated similar susceptibility to motion.
2. Shinde, S. V.; Sonavane, S. S. "Development of electronic tattoo for pulse rate monitoring: Materials perspective" AIP, vol. 1966, no. 1, 2018. [Online]. Available: <https://doi.org/10.1063/1.5038686>. [Accessed Oct. 28, 2019]
 - a. In pursuit for development of Electronic Tattoos (ET), this group came across various designs and candidate materials which can be used for the ET. In this paper, they describe the process of selecting best suited method and material for the ET. It may also be noted that the sensor development is governed by the prevailing IEEE 802.15.6 standard.

3. Wang, Y.; Qiu, Y.; Ameri, S. K. "Low-cost, μm -thick, tape-free electronic tattoo sensors with minimized motion and sweat artifacts" *npj Flexible Electronics*, vol. 2, no. 6, February 13, 2018. [Online]. Available: <https://doi.org/10.1038/s41528-017-0019-4>. [Accessed Oct. 29, 2019]
 - a. This paper reports a cut-and-pasted e-tattoo that is only $1.5\ \mu\text{m}$ thick and can be directly pasted on human skin like a temporary transfer tattoo. This e-tattoo is tape-free and designed into an open-mesh filamentary structure, which makes it breathable and exhibit negligible stiffness. It includes multiple sensors and can synchronously measure skin temperature, skin hydration, and electrocardiogram (ECG).
4. Qiao, Y.; Wang, Y.; Li, M. "Multilayer Graphene Epidermal Electronic Skin" *ACS Nano*, vol. 12, no. 9, July 24, 2018. [Online]. Available: <https://doi.org/10.1021/acsnano.8b02162>. [Accessed Oct. 29, 2019]
 - a. This work demonstrates a multilayer graphene epidermal electronic skin based on laser scribing graphene, whose patterns are programmable. A process has been developed to remove the unreduced graphene oxide. This method makes the epidermal electronic skin not only transferable to butterflies, human bodies, and any other objects inseparably and elegantly, merely with the assistance of water, but also have better sensitivity and stability. Therefore, pattern electronic skin could attach to every object like artwork. To provide a deeper understanding of the resistance variation mechanism, a physical model is established to explain the relationship between the crack directions and electrical characteristics. The results of this research show that graphene epidermal electronic skin has huge potential in health care and intelligent systems.
5. Ameri, S. K.; Kim, M.; Kuang, I. A. "Imperceptible electrooculography graphene sensor system for human-robot interface" *npj 2D Materials and Applications*, vol. 2, no. 19, July 24, 2018. [Online]. Available: <https://doi.org/10.1038/s41699-018-0064-4>. [Accessed Nov. 1, 2019]
 - a. This paper reports an imperceptible EOG sensor system based on noninvasive graphene electronic tattoos, which are ultrathin, ultrasoft, transparent, and breathable. The GET EOG sensors can be easily laminated around the eyes without using any adhesives and they impose no constraint on blinking or facial expressions. High-precision EOG with an angular resolution of 4° of eye movement can be recorded by the GET EOG and eye movement can be accurately interpreted. Imperceptible GET EOG sensors have been successfully applied for human-robot interface (HRI). To demonstrate the functionality of GET EOG sensors for HRI, this group connected GET EOG sensors to a wireless transmitter attached to the collar such that they can use eyeball movements to wirelessly control a quadcopter in real time.

6. Park, R.; Kim, H.; Lone, S. "One-Step Laser Patterned Highly Uniform Reduced Graphene Oxide Thin Films for Circuit-Enabled Tattoo and Flexible Humidity Sensor Application" MDPI, vol. 18, no. 6, June 6, 2018. [Online]. Available: <https://doi.org/10.3390/s18061857>. [Accessed Nov. 1, 2019]
 - a. This research conveys a facile deposition process of GO on flexible polymer substrates to create highly uniform thin films over a large area by a flow-enabled self-assembly approach. The self-assembly of GO sheets was successfully performed by dragging the trapped solution of GO in confined geometry, which consisted of an upper stationary blade and a lower moving substrate on a motorized translational stage. The prepared GO thin films could be selectively reduced and facilitated from the simple laser direct writing process for programmable circuit printing with the desired configuration and less sample damage due to the non-contact mode operation without the use of photolithography, toxic chemistry, or high-temperature reduction methods. Furthermore, two different modes of the laser operating system for the reduction of GO films turned out to be valuable for the construction of novel graphene-based high-throughput electrical circuit boards compatible with integrating electronic module chips and flexible humidity sensors.
7. Ferrari, L. M.; Sudha, S.; Tarantino, S. "Ultraconformable Temporary Tattoo Electrodes for Electrophysiology" Advanced Science, vol. 5, no. 3, January 3, 2018. [Online]. Available: <https://doi.org/10.1002/advs.201700771>. [Accessed Nov. 1, 2019]
 - a. In this work, dry, unperceivable temporary tattoo electrodes are presented. Customized single or multielectrode arrays are readily fabricated by inkjet printing of conducting polymer onto commercial decal transfer paper, which allows for easy transfer on the user's skin. Conformal adhesion to the skin is provided thanks to their ultralow thickness ($<1\ \mu\text{m}$). Tattoo electrode-skin contact impedance is characterized on short- (1 h) and long-term (48 h) and compared with standard pregelled and dry electrodes. The viability in electrophysiology is validated by surface electromyography and electrocardiography recordings on various locations on limbs and face. A novel concept of tattoo as perforable skin-contact electrode, through which hairs can grow, is demonstrated, thus permitting to envision very long-term recordings on areas with high hair density. The proposed materials and patterning strategy make this technology amenable for large-scale production of low-cost sensing devices.

8. Lu, N.; Ameri, S. K.; Ha, T. "Epidermal electronic systems for sensing and therapy" SPIE Digital Library, 10167, April 17, 2017. [Online]. Available: <https://doi.org/10.1117/12.2261755>. [Accessed Nov. 4, 2019]
 - a. This research team has invented a cost and time effective, completely dry, benchtop "cut-and-paste" method for the green, freeform and portable manufacture of epidermal electronics within minutes. They have applied the "cut-and-paste" method to manufacture epidermal electrodes, hydration and temperature sensors, conformable power-efficient heaters, as well as cuffless continuous blood pressure monitors out of metal thin films, two-dimensional (2D) materials, and piezoelectric polymer sheets. Three examples of "cut-and-pasted" epidermal electronic systems are discussed in this paper. The first is submicron thick, transparent epidermal graphene electrodes that can be directly transferred to human skin like a temporary transfer tattoo and can measure electrocardiogram (ECG) with signal-to-noise ratio and motion artifacts similar to conventional gel electrodes. The second is a chest patch which houses both electrodes and pressure sensors for the synchronous measurements of ECG and seismocardiogram (SCG) such that beat-to-beat blood pressure can be inferred from the time interval between the R peak of the ECG and the AC peak of the SCG. The last example is a highly conformable, low power consumption epidermal heater for thermal therapy.
9. Lipovka, A.; Murastov, G.; Nozdrina, O. "Electronic Tattoos for Health Tracking based on Graphene Oxide" Unknown, 2017. [Online]. Available: http://earchive.tpu.ru/bitstream/11683/45504/1/conference_tpu-2017-C17_p123-124.pdf. [Accessed Nov. 5, 2019]
 - a. This work describes the advantages that are available due to the properties of graphene oxide: optical transparency, mechanical and chemical stability, biocompatibility. Suggested Etattoos could be applied for several measurements, for example: ECG, EEG, EMG, temperature measurements. Experimental data shows that the principle possibility of the rGO patterns fabrication for the future application in the wearable tattoo-like sensors. The obtained results give the suitable parameters to work with laser patterning at the future stages.
10. Jeong, H.; Lu, N. "Electronic tattoos: the most multifunctional but imperceptible wearables" SPIE Digital Library, 11020, 2019. [Online]. Available: <https://doi.org/10.1117/12.2518994>. [Accessed Nov. 5, 2019]
 - a. This paper introduces a low-cost, dry and freeform "cut-and-paste" and "cut-solder-paste" method invented by their lab to fabricate e-tattoos. This method has been proved to work for thin film metals, polymers, ceramics, as well as 2D materials. Using this method, researchers created the first truly imperceptible e-tattoos based on graphene, and modular and reconfigurable Bluetooth and NFC enabled wireless e-tattoos.