Three-dimensional bioelectronics

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Complex engineered systems are typically built as sum of parts where each part serves its own unique functions. As an example, an electronic transistor is put in a chip (space) and clocked (time) to perform say a logic switching function; a pH sensor is designed to sense pH from its environment, *etc.* Nature, on the other hand, is quite frugal and seems to have abondoned the sum-of-parts model. Evolution seems to have preferred a more wholesome approach to design: each part serves more than one function in the whole organism where the whole is also contained in the part. Let us take the example of cardiac cells in your heart; each cell contributes to the organ/structure (ventricles, valves) of the heart, provides mechanical strength (stretchability and flexibility), is in state of constant actuation (beating of the heart) and provides electrical connectivity to the rest of the heart and the brain. What it does is even remarkable allowing our heart to beat more than 35 million times/year to keep us alive.

So we ask whether we can engineer a bioelectronic interface that is true to nature in its design and spirit? *Can we make a device that can provide all the functions (structure,electronics, sensing, actuation) in one?* The answers to this question will have a strong impact. In our example of cardiac tissue implant, it will allow us its mechanical structural and electrical functions. Current solutions for cardiac implant utilize different material systems for structural support, sensing and electronics, all patched together in a system that is not compatible with the host tissue and with one another.

Our current solution is a liquid-gated three-dimensional graphene (3DG) foam [1–4]. The natural fluid in the tissue microenvironment serves as electrolyte for transistor gating. A single 3DG device can monitor multitude of physical and chemical parameters. We already have encouraging results that it can measure local field potential (electrical activity), local physical force (strain, temperature) and biochemicals (pH, glucose) in its microenvironment. The 3DG foam is highly biocompatible and serves as a scaffold for cell growth and proliferation. Graphene, due to its naturally carbonaceous form, is amazingly lightweight, biocompatible, has high tensile strength, and is extremely transparent over a wide optical window. Its carbon nature provides access to a rich surface chemistry for chemical and biological functionalization using enzymes, antibodies or aptamers for sensing. Not to mention that it provides useful electronic functions as a transistor. In this work, I will showcase our existing work on this multifunctional 3DG for 3D bioelectronics interface and discuss the roadmap with needs and possible candidates for the future of this field.

1. S. K. Ameri *et al.*, "Flexible 3D graphene transistors with ionogel dielectric for low-voltage operation and high current-carrying capacity", *Adv. Electronic Mater.* **2**, 1500355 (2016).
2. S. K. Ameri, P. K. Singh, and S. R. Sonkusale, "Liquid gated three dimensional graphene network transistor", *Carbon* **79**, 572 (2014).
3. S. K. Ameri, P. K. Singh, and S. R. Sonkusale, "Three dimensional graphene transistor for ultra-sensitive pH sensing directly in biological media", *Anal. Chim. Acta* **934**, 212 (2016).
4. S. K. Ameri *et al.*, "Three dimensional graphene scaffold for cardiac tissue engineering and in-situ electrical recording", *Proc. IEEE EMBC* (2016), pp 4201–3.