Multiple pathways to stretchable electronics

Stretchable conductors expand the interfaces with biological structures

By Tarek Rafeedi and Darren J. Lipomi

The aim of stretchable electronics is often to integrate complex multifunctional devices with biological structures (1–3). To achieve this, devices need to conform to and deform with the body’s anatomy (e.g., skin, internal organs, blood vessels, and nerves) while maintaining their electronic function (e.g., monitoring changes in a biological milieu or supplying stimulus to it). On page 1222 of this issue, Zhao et al. (4) report a device that can reliably interface with biological substrates while being stretched. Their work demonstrates a platform for fabricating elastic bioelectrodes based on microcracked conductive polymers. The authors apply four different bio-compatible materials to this platform, creating a library of biosensors and stimulators.

Solids are deemed stretchable if they considerably deform (strain) under applied force (stress) and return to their original shape when the force ceases. Further, the ability of materials to stretch while retaining their electronic function is intimately related to their structure. The mechanical and electronic properties of a certain material arise from the precise arrangement of its atoms or molecules and the types of bonds formed between them, be they metallic, covalent, electrostatic, or van der Waals. Changing the atomic spacing or bond strength through the application of mechanical stress usually affects electronic properties. Thus, the key to stretchable electronics lies in materials and device layouts that can accommodate large strain in ways that do not hinder charge transport.

Many approaches have been explored to combine conductivity and stretchability, often following the motifs of making a conductive stretchy or making an elastomer material conductive. Superimposing these properties involves engineering them such that they do not, or only minimally, interfere. There are four broad strategies that have been used to make stretchable devices for biomedical applications, two of which are used by Zhao et al. (see the figure).

The first approach is to incorporate a conductive filler in an insulating elastomeric carrier (5, 6). Conductive fillers that have been used successfully include metallic particles (e.g., nanospheres, liquid metal droplets, and...
The fourth approach, highlighted by Zhao et al., is the use of microcracked films. They used a laminate of strain-fractured plates of a rigid conductor and an auxiliary conductive composite film containing vertically oriented wires. When the structure is stretched, the cracks in the rigid films expand, yet the vertically oriented wires preserve connectivity between the cracked plates. There have been other applications of this deliberate fracture and bridging strategy for conformal biological electrodes (14, 15); what differentiates this work is the breadth of possible applications afforded by the range of materials used.

The main challenge in applying cracked films to stretchable devices is that electrical resistance is not invariant to strain. That is, when the material is strained, the cracks expand, leaving tortuous paths for the charge to flow, which increases the in-plane electrical resistance. To overcome this limitation, Zhao et al. integrate orthogonal conductive pathways using conductive fillers—making the in-plane conductivity invariant to strain. These microcracked conductors can be applied conformally to a biological substrate while maintaining a constant contact area by expanding the preformed cracks. This constant and conformal contact ensures that electrical signals from and to the electrode-anatomy interface remain intact. To demonstrate these effects, the authors report a variety of applications, including in vivo neurostimulation of a mouse sciatic nerve and in vitro electrochemical sensing of pH and select chemical compounds. They demonstrate that, in the stretched state, the bioelectrodes operate with unvarying fidelity.

The approach of Zhao et al. embodies the moniker of stretchable electronics, which is often used loosely and perhaps imprecisely in the field. Almost anything can be stretched, but many materials are destroyed in doing so. Their approach acknowledges the damage caused by strain and exploits it to a positive effect—creative destruction.

REFERENCES AND NOTES

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SYNTHETIC BIOLOGY
Engineering time-controlled immunotherapy
Designer lymphocytes expand the dynamic range of possibilities for treating disease

By Emanuel Salazar-Cazavos and Grégoire Altan-Bonnet

Immunotherapy harnesses the immune response to treat diseases, from cancers to autoimmune disorders. The boundaries of clinical immunotherapy for cancer have been pushed by the development of cancer-killing T cells that target tumors, therapies that block immune checkpoints to rearm cytotoxic T cells, and the optimization of engineered chimeric antigen receptor (CAR) T cells (1). But there remain limitations when immune functions that have evolved to clear fast-invading pathogens are repurposed to eradicate slow-growing tumors. On pages 1186 and 1227 of this issue, Allen et al. (2) and Li et al. (3), respectively, present synthetic biology-based strategies to further improve cancer immunotherapies. Rather than being limited by “natural” immunology (using leukocytes, antibodies, and cytokines), these studies expand the scope of immune responses elicited by CAR T cells against diseased tissues.

Current CAR T cell therapies involve ex vivo engineering of patient T cells to express CARs that recognize specific molecules on the surface of tumors, before they are injected into patients. However, immune responses develop over long time scales (>1 week), such that immunotherapies that are optimized for short-term cellular responses (e.g., killing of tumor cells) may not achieve long-term systemic solutions (e.g., eradication of tumors) (4). Indeed, postinjection interventions to increase CAR T cell activity are limited because immune perturbations and synthetic circuits that allow precise control of cell functions over time and in clinical set-
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