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Materials and Techniques for Implantable Nutrient Sensing Using Flexible Sensors Integrated with Metal–Organic Frameworks

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The combination of novel materials with flexible electronic technology may yield new concepts of flexible electronic devices that effectively detect various biological chemicals to facilitate understanding of biological processes and conduct health monitoring. This paper demonstrates single- or multichannel implantable flexible sensors that are surface modified with conductive metal–organic frameworks (MOFs) such as copper-MOF and cobalt-MOF with large surface area, high porosity, and tunable catalysis capability. The sensors can monitor important nutriments such as ascorbic acid, glycine, L-tryptophan (L-Trp), and glucose with detection resolutions of 14.97, 0.71, 4.14, and 54.60 × 10^{-6} M, respectively. In addition, they offer sensing capability even under extreme deformation and complex surrounding environment with continuous monitoring capability for 20 d due to minimized use of biological active chemicals. Experiments using live cells and animals indicate that the MOF-modified sensors are biologically safe to cells, and can detect L-Trp in blood and interstitial fluid. This work represents the first effort in integrating MOFs with flexible sensors to achieve highly specific and sensitive implantable electrochemical detection and may inspire appearance of more flexible electronic devices with enhanced capability in sensing, energy storage, and catalysis using various properties of MOFs.

The emerging flexible electronics technology offers excellent solutions to construct lightweight and ultrathin implantable devices that can be used to conduct continuous monitoring of analytes in different body fluids and organs to gain profound insights of biophysiological processes[1] and reveal underlying mechanisms of various diseases.[2] The advantages of flexible implantable devices involve reduced tissue damage and conformable tissue contact, leading to high measurement sensitivity and repeatability. In addition, bioinspired flexible tentacle-like structures, which contain bendable and deformable channels scattering from a center controller, can also be constructed, leading to multichannel sensing capability for different body or organ locations.

Flexible sensors are notable for their sensing abilities of physical properties such as heart rate,[3] biopotential,[4] temperature,[4] and skin impedance.[5] However, chemical detection using flexible sensors are still largely unexplored other than some notable demonstrations in detecting glucose,[6] lactate,[7,8] and electrolytes.[7,9] Despite excellent adaptability to various surface morphology and environmental conditions, the chemical sensing capability in terms of resolution, specificity, and reliability of flexible sensors may not necessarily outweigh electronic devices based on rigid composition materials.

A promising approach to improve the chemical sensing capability of flexible sensors involves combining these devices with wild ranges of functional materials that offer unique properties to facilitate chemical analysis,[10] resulting in combined advantages both from the functionality of the materials and soft, flexible mechanics of the sensors. A large category of functional materials that have not yet been explored in flexible electronics are metal–organic frameworks (MOFs), which are essentially inorganic–organic hybrids that contain repeated metal ions connected with organic ligands. MOFs are notable for their large surface area, highly porous structures, and tunable catalysis capability, all of which are highly demanded for biological sensing. When proper organic ligands are chosen, MOFs can be conductive or semiconductive, leading to development of several electronic devices such as field effect transistors,[11] electric double-layer capacitors,[12] and sensors.[13,14] Despite various demonstrations of MOFs in chemical sensing, they have never been demonstrated in implantable biological

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