Power Sources for Sensors and Robots in Remote and Inaccessible Environments

by
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The continuous shrinkage of size and the drop of cost have greatly enlarged the application space for sensors and robots based on electronic device. They are being deployed ever further, into environments that were too remote or too confined to be accessed before. The harsh environmental conditions or the extreme size constraints have raised considerable challenge in creating suitable power sources for robots. This thesis works towards addressing the energy demand for sensors in those inaccessible environments, and by extension exploring their potential applications. In specific, we approach this goal in 2 aspects.

On one hand, we developed and optimized thermal energy harvesting systems to power wireless sensor nodes in remote locations such as desert and underground environment where solar power is not reliable. We combined theory and experiments to improve the efficiency of these thermal energy harvesters, by optimizing material properties, device configurations and employing nonlinear thermal devices. In the first work, we present a mathematical theory for the operation and design of a thermal resonator interfaced with thermal diodes on its external boundaries with the environment. We show that such a configuration is potentially able to produce single polarity temperature difference drastically exceeding that of previously reported thermal resonators by a factor of 5. In collaboration with an international team, we have demonstrated the integration of thermal resonators with batteries for energy storage, and with RF energy harvester to power a temperature sensor.

On the other hand, we created picoliter sized Zn-air batteries to provide on-board power for microscopic sensors that can enter highly confined spaces such as the blood vessel and the brain tissue. We overcome the material and fabrication difficulties to create batteries with linear dimensions on the order of 10 μm, providing remarkable energy density of 2.75 μJ/pL (or 760 Wh L^{-1}). The parallel nature of photolithography processes allows 10,000 devices per wafer to be released into solution as colloids with energy stored onboard. Within a volume of only 2 pL each, these primary microbatteries can deliver open circuit voltages of 1.05 ± 0.12 V with a maximum power near 2.7 nW. We demonstrate that such systems can reliably power a micron-sized memristor circuit, providing access to non-volatile memory. We also cycle power to drive the reversible bending of microscale actuators at 0.05 Hz for mechanical functions of colloidal robots. Additional capabilities such as powering two sensors made of nano-materials and a clock circuit are also demonstrated.

Solving the energy problem paves the way for creating cell-sized autonomous sensors that can collect the information non-invasively in narrow channels like blood vessels and digestive tracts. Hence, we explored theoretically the possibility of using micro-robots to detect leaks inside tubes, revealing one corner of the tremendous potential of microscopic machines. Interior information of the reactors can be extracted from smart tracer particles that record the local concentration when travelling through the reactors. Integrating the recordings from multiple tracers with their residence time, we demonstrate for the first time that the concentration profile inside a tubular reactor can be mapped out, without any prior knowledge or models for the reactor. Using numerical simulation, the effects of design parameters, such as number of tracers and sampling frequency, on the fitting

accuracy were studied. We also discussed the impact of non-idealities on the fitting, including limited storage capability, severe particle diffusion and sensor noise.

Finally, we investigated the theory and reaction mechanisms of 2D polymers, which can guide the synthesis of low permeability materials for sealing leaks. We perform a chemical kinetic simulation to study the synthesis of 2D polymers in homogeneous solution with irreversible chemistry recently realized by our lab. We show that reaction sites for polymerization in 2D always scale unfavourably compared to 3D, growing as molecular weight to the 1/2 power versus 2/3 power for 3D. However, we have identified two mechanisms that can effectively suppress out-of-plane defect formation and subsequent 3D growth, which we call *bond-planarity* and *templated autocatalysis*. In the first mechanism, although single bonds can easily rotate out-of-plane to render polymerization in 3D, some double-bond linkages prefer a planar configuration. In the second mechanism, stacked 2D plates may act as van der Waals templates for each other to enhance growth, which leads to an autocatalysis. We map the dependence of molecular weight and yield for 2D polymer on the reaction parameters, allowing experimental results to be used to our simulation results.

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