Marine biology requires new line of inquiry in materials research

By **Zhen Zhang**, **Bruce H. Robison**, and **Shriram Ramanathan**

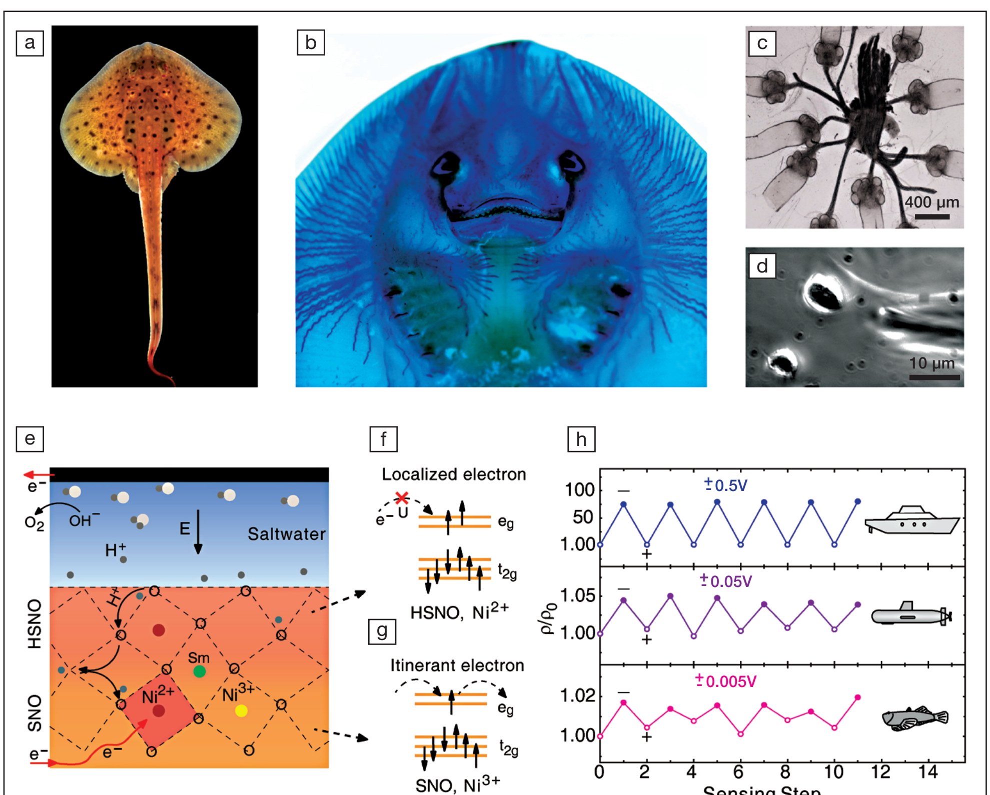
Although oceans cover nearly 70% of the planet, they comprise the least understood of Earth's major ecosystems. Oceans have been an important sustainer of life on Earth and promise vast future potential for overcoming current grand challenges in energy, food, global climate, and sustainability. However, current knowledge of oceanic ecosystems is limited by the complexity involved in exploring and sensing harsh marine environments.

Historically, the needs of the military to monitor surface and undersea vessels drove early developments in acoustic and magnetic field sensors,[1,2] and sonar has long supported the commercial fishing industry. Oceanographers require information on physical and chemical properties such as temperature, salinity, oxygen concentration, acidity, and pressure to understand climate change effects. There is also great interest among marine biologists to assess and understand different forms of life at various depths of the ocean and how the local populations interact and change over time.

Sampling even a small fraction of the planet's vast oceans requires the design of sensors that can be deployed from ships and robots and on autonomous vehicles or submersible floats that operate long-term. They also have the ability to transmit data directly or by satellite. For example, the Argo project—a global array of 3800 free-drifting profiling floats—has successfully collected basic information such as ocean temperature and salinity over the past two decades by deploying thousands of sensors in various oceans across the planet.[3]

Designing functional materials to operate in ocean environments, such as for sensing applications, presents a formidable challenge. The materials have to be corrosion-resistant, but should not form passive layers that inhibit information transfer or sensing capability. Sensors must be pressure-tolerant and resistant to biofouling, as well as use low levels of power. Preferably, they should be calibration-stable over extended periods of time to be deployable on autonomous platforms.

Researchers can look at nature to better guide materials design. Over millions of years, in order to adapt to challenging marine environments, marine animals have evolved remarkable sensory systems such as echolocation in toothed whales



The electroreception organ of the elasmobranch species and its emulation by oxide quantum materials. (a) A skate's dorsal profile. (b) Ampullary organ canals stained by Alcian blue. (c) Ampullary organs with nerve fibers attached. (d) Image of electrosensory cells. (e) Electric-field-induced hydrogenation of $SmNiO_3$. (f–g) Electronic structure of Ni 3*d* orbital of $SmNiO_3$ in (g) pristine and (f) hydrogenated states where electrons become localized. (h) Modulation of electrical resistivity of $SmNiO_3$ in saltwater after applying bias potential (±0.5~±0.005 V) over several cycles. (a–d) Images are reprinted with permission from Reference 5. (e–h) Images are reprinted with permission from Reference 7.

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(i.e., odontocetes), low-light vision in deep-sea fish, and mechanoreceptors in lateral lines of aquatic vertebrates. This naturally presents a great source of inspiration for materials researchers concerned with water interfaces.

Marine organisms such as elasmobranchii (sharks, skates, and rays) have evolved sensors to recognize the electrical and chemical nature of their environment by an electroreception organ, commonly known as *ampullae of Lorenzini* (AoL).[4] The AoL is typically arrayed on the head of elasmobranch species (see **Figures a–d**),[5] and this organ enables detection of weak electrical signals emitted by prey fish or generated by ocean currents. Weak electrical signals transmit through highly conductive gel-filled canals (**Figure b**) to electrosensory cells at the bottom membrane of the AoL (**Figures c–d**). Electric-bias-induced ion exchange through these sensing cells trigger neuronal activity for information transmission concerning the immediate environment.[4,6] Recent research on perovskite nickelates (e.g., $SmNiO_3$) suggests a synthetic analogue to emulate both the microscopic mechanism as well as functionality of AoL.[7] $SmNiO_3$ (SNO) detects electrical signals amplified by a phase transition caused by electric-field-induced hydrogenation from water (**Figures e–h**).

Besides this example, several areas in the marine sciences can benefit from advanced materials. For instance, identifying species-specific chemical or biological fingerprints of marine animals *in situ* would greatly enhance understanding their presence, passage, and ecological interactions. This can also help biologists understand how climate change and excessive fishing by humans affect the oceanic food web. Changing ocean ecosystems have both immediate and long-term repercussions on the quality of life for those reliant on fisheries to supply their food or livelihood.

Materials that are stable in water and can exchange information between fluidic media and an external circuit through sensory interfaces can be game-changing for understanding the oceans. This requires fundamental research on interface science that bridges soft–hard materials systems, ionic-electronic current transduction, and sensitivity to bio-matter, long-term stability, and preferably the read-out of signals in a noncontact manner (e.g., optical signaling). Multidisciplinary research is necessary to tackle the important societal problems for which advanced materials are a key ingredient.

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