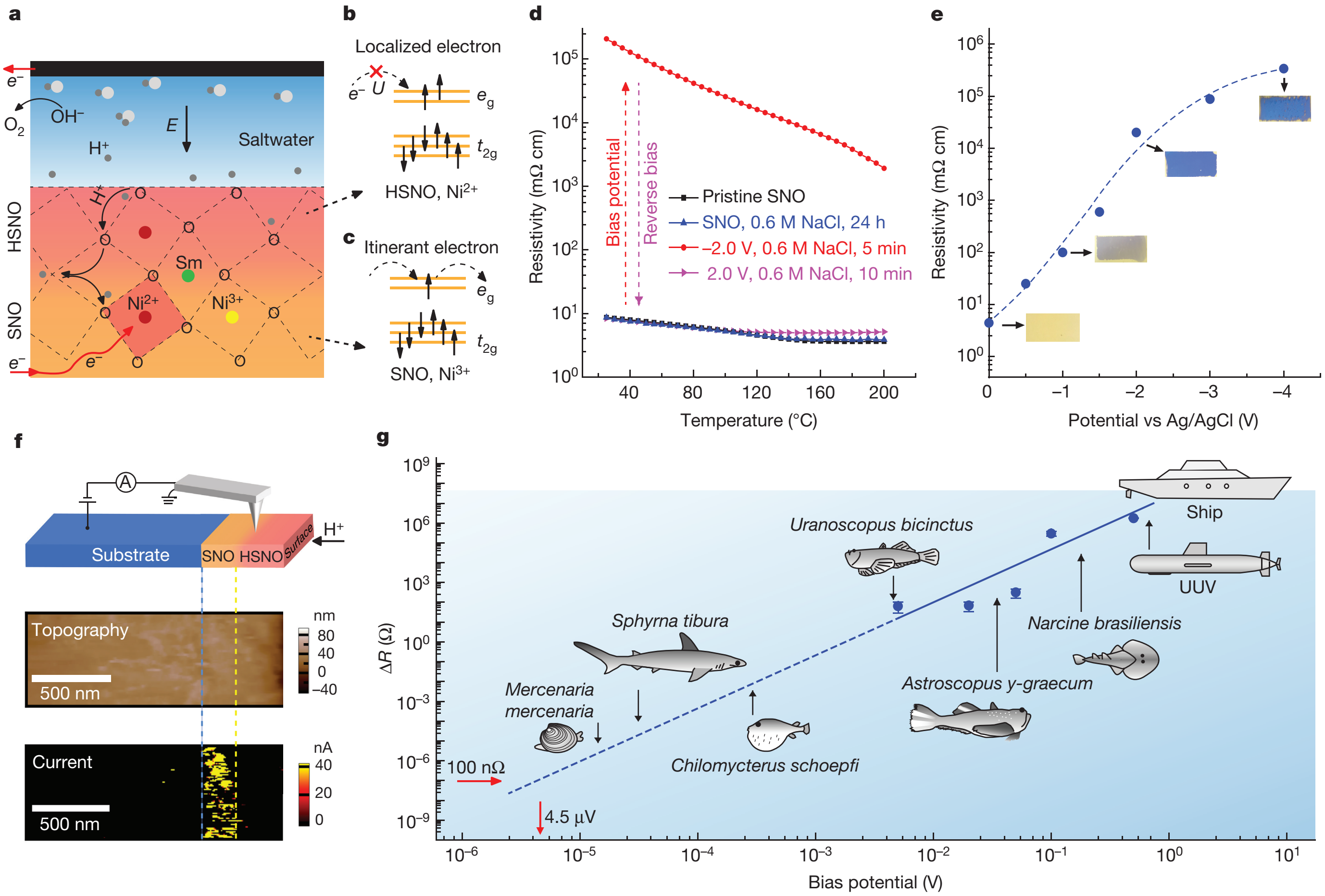

Figure 1 | Saltwater-submersible nickelate sensors. **a**, Illustration of the saltwater-mediated phase transition in SNO. Under bias, the protons intercalate and diffuse into the SNO lattice accompanied by electron transfer from the counter-electrode (*E*, electric field). **b**, **c**, Schematics of the electronic structure of Ni 3*d* orbitals in hydrogenated (**b**) and pristine (**c**) SNO. The electrons become localized in HSNO owing to the strong Coulomb repulsion in doubly occupied e_g orbitals above the t_{2g} orbitals. *U* represents the on-site electron–electron correlation. **d**, After being submerged in a 0.6 M NaCl solution for 24 h at room temperature, the electrical resistivity of SNO is similar to that of pristine SNO, indicating its robustness in water. The red curve shows increased electrical resistivity after applying a negative bias of −2.0 V in a 0.6 M NaCl solution for 5 min. The sample is then treated under a reverse bias of 2.0 V for 10 min, and its electrical resistivity curve (purple) is almost recovered to its original state. **e**, Electrical resistivity and colour change of SNO thin films after applying various bias potentials in a 0.6 M NaCl solution for 10 s. **f**, Cross-sectional conducting AFM images of SNO after bias treatment, showing reduced current owing to the phase change. **g**, The experimentally observed change in the electrical resistance (Δ*R*) for bias potentials from 0.5 V to 5 mV (Extended Data Fig. 2c). This measurement range spans all maritime vessels and several marine animals, as marked. The resistance change beyond the present measurement window (<5 mV) is estimated by linear extrapolation. With high-resolution resistance measurements (100 nΩ; see Methods), the SNO device would be sensitive down to about 4.5 μV, extending to even smaller marine animals[11–16]. Error bars show standard deviations. UUV, unmanned underwater vehicle.

colour, HSNO) propagates into the SNO thin film from the water interface, indicating the intercalation and diffusion of protons into SNO during sensing. Additional conducting AFM images taken in-plane (Extended Data Fig. 3 and Supplementary Information section 3) further rule out corrosion or morphological degradation during water treatment as the origin of the resistance change and demonstrate the uniformity and diffusional nature of the water-mediated phase transition in SNO.

The water-treated thin films can be brought back to the low-resistivity state by the application of a reverse bias (Fig. 1d and Extended Data Fig. 1a, purple curve), indicating their capability to detect local fluctuations of an electric potential in water. We find that the electrical resistivity of SNO can change consistently following the application of a bias potential ranging from ±0.5 V to ±0.005 V over multiple cycles (Extended Data Fig. 2c). Figure 1g shows the modulation of the electrical resistance of SNO when a bias potential down to the level of millivolts is applied to evaluate the measurement sensitivity of SNO. The sensitivity of our SNO device can be extrapolated to show a microvolt-level detection ability in oceans, which is enabled by high-resolution resistance measurements (see Methods) in the entire range of bioelectric potentials generated by numerous marine species up to galvanic potentials from ships and unmanned underwater vehicles[11–16].

The sensing mechanism of SNO is analogous to the electroreception organs of elasmobranch species such as sharks, rays and skates: the ampullae of Lorenzini[17–19]. These ampullae are located around the mouths of sharks[20]; the distinctive structure of a single ampulla is shown schematically in Extended Data Fig. 2d. The jelly inside the ampulla, which has excellent proton conductivity[21] and enables thermal sensing[22], conducts ions from the nearby sea water to the membrane located at the bottom of the ampulla. The membrane contains sensing cells that react to an electric potential applied across them (Extended Data Fig. 2d). Under electric bias, ionic channels on the apical side of the sensing cells open and allow a flux of charged ions, which causes the sensing cell to release neurotransmitters to synapses at the bottom, informing the brain[17,20]. Thus, the ampullae of Lorenzini enable these sharks to detect bioelectric fields emitted by prey fish[18]. This suggests an analogy between the nickelate sensor and the electroreception organ of sharks. We calculated the detection distance of SNO and found a similar length scale to what has been reported for the elasmobranch electroreceptors (Extended Data Fig. 2e). Furthermore, the response

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