Performance modulation of $\alpha$-MnO$_2$ nanowires by crystal facet engineering

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Performance modulation of material physical and chemical properties through selective surface engineering is currently one of the most active research fields, aimed at optimizing functional performance for applications. The activity of exposed crystal planes determines the catalytic, sensory, photocatalytic, and electrochemical behavior of a material. In the research on nanomagnets, it opens up new perspectives in the fields of nanoelectronics, spintronics, and quantum computation. Herein, we demonstrate controllable magnetic modulation of $\alpha$-MnO$_2$ nanowires, which displayed surface ferromagnetism or antiferromagnetism, depending on the exposed plane. First-principles density functional theory calculations confirm that both Mn- and O-terminated $\alpha$-MnO$_2$ (1 1 0) surfaces exhibit ferromagnetic ordering. The investigation of surface-controlled magnetic particles will lead to significant progress in our fundamental understanding of functional aspects of magnetism on the nanoscale, facilitating rational design of nanomagnets. Moreover, we approved that the facet engineering pave the way on designing semiconductors possessing unique properties for novel energy applications, owing to that the bandgap and the electronic transport of the semiconductor can be tailored via exposed surface modulations.

The morphology related properties of nanomaterials have attracted growing research interest for generating peculiar properties with great potential for practical innovative applications$^{1–5}$. Crystal facet engineering is known to induce exotic physical and chemical performance in functional materials due to the distorted electronic structure and different exposed ions in the surface layers of inorganic crystals with different exposed planes$^{6–9}$. Scientific and technological exploration has shown the profound influence of such surface layer in research on catalysis and photocatalysis. Xie et al. found that the (1 1 0) facet exposed Co$_2$O$_4$ nanorods had the ability to catalyze CO oxidation at temperatures as low as 77K, because the (1 1 0) planes expose active Co$^{3+}$ species at the surface and allow the CO oxidizes at Co$^{3+}$ sites at such a low temperature$^6$. In research on photocatalysis, anatase TiO$_2$ showed promise for energy and environmental applications if the active (0 0 1) planes were exposed on the surface$^7$. Tian et al. synthesized platinum nanocrystals with an unusual tetrahedral shape, with the polyhedra enclosed by 24 high-index facets, such as (7 3 0) and (5 2 0) surfaces with high density of atomic steps and dangling bonds. These surfaces exhibit enhanced catalytic activity compared to equivalent conventional Pt surfaces towards electro-oxidation of small organic molecules such as ethanol and formic acid$^{8}$. Thereafter, Zhang et al. investigated the catalytic reaction processes of triiodide reduction over [1 0 0], [1 1 1] and [4 1 1] facets of Pt, indicating that the activity follows the order of Pt(1 1 1) > Pt(4 1 1) > Pt(1 0 0) using density functional theory$^9$. The highest photovoltaic conversion efficiency of Pt(1 1 1) in dye-sensitized solar cells confirms the predictions of their theoretical study with the understanding of the mechanism of triiodide reduction at Pt surfaces$^9$. The distorted electronic structure in the surface layer also induces exotic physical phenomena in the conductivity and magnetic coupling. The topological insulator is one such example of unique surface behavior$^{10}$. The electronic band structure in the bulk of a non-interacting topological insulator resembles that of a normal insulator with the Fermi level falling in the gap of the conduction and valence bands. While the surface of a topological insulator shows special states falling within the bulk energy gap and allowing surface metallic conductive behavior. Lu et al demonstrated the influence of facet effect on electrochemical performance of one-dimensional SnS nanobelts grown along the [0 2 0] direction and expose (1 0 0) facets$^{11}$. The SnS nanobelts also showed unexpected strong photon absorption properties from the ultraviolet to the near-infrared region.
It is expected that facet engineering might be a possible way to modulate magnetism, because the magnetism is determined by the short-range interaction between the magnetic ions. The short-range interaction depends on the bond length, bond angle, and coordination environment of the magnetic ions. Facet engineering can tune these parameters through surface reconstruction to control the magnetic behavior. Indeed, Ohnishi et al demonstrated theoretically that in iron the magnetic moment increases from 0.73 μB/atom in the center layer to 2.98 μB/atom in the surface layer of an Fe (0 0 1) plane22. For the transition metal oxides, such as manganese oxides, the bond angle of Mn-O-Mn is 180° in the MnO2 octahedral environment. The Mn ions are antiferromagnetically coupled through the O superexchange interaction. On the other hand, the bond angle of Mn-O-Mn is 90° in the MnO2 tetraedral environment. Mn-Mn can then show ferromagnetic coupling behavior through Heisenberg exchange coupling23. Our previous work indicates that x-MnO2 nanowires exposed (2 1 0) planes on the side walls show extrinsic spin-glass performance with exchange-bias behaviour14.

This work demonstrates that the magnetism and electrochemical properties of x-MnO2 nanowires can be modulated by exposing different crystal planes on the surface. We synthesized two batches of x-MnO2-based nanowires, one with exposed (1 1 0) planes on the side walls (defined as MnO2-110) and the other with exposed (2 1 0) planes on the side walls (defined as MnO2-210). It is interesting that the exposed surfaces of MnO2 show significant influences on the magnetic and electrochemical properties of the materials. Magnetic measurements clearly demonstrate that MnO2-110 is ferromagnetic (FM) and MnO2-210 is mainly antiferromagnetic (AFM). Density functional theory (DFT) calculations confer the different types of surface magnetism in these two samples. Collectively, we demonstrate two distinct sources contributing to the magnetism in the nanostructures: antiferromagnetic ordering in the core region and tuneable surface magnetism, which is mainly attributed to the surface Mn ions. It is also demonstrated that different exposed surfaces endow unique photocatalyst and lithium battery applications of x-MnO2 nanowires. The energy-related applications of x-MnO2 nanowires have been studied by taking advantage of the big size of the (2 × 2) tunnels along the c-axis as ion/molecule channels21–23, but the other possibility of their use as magnetic nanowires (MNNs) has been largely unexplored. Inspired by the intriguing structure of x-MnO2, naively, one may envisage that by selective cutting of the (2 × 2) tunnels along the planes with low Miller indices, such as (1 1 0) and (2 1 0)22,25, the tunnel structure of x-MnO2 may be opened up, and consequently, different magnetic and electrochemical performances could be obtained. This reveals a possible route towards the selective modulation of the magnetic and chemical properties in nanostructured x-MnO2.

Results and Discussion

Phases, microstructure, and valence state. Both samples are high purity x-MnO2, as indicated by the X-ray diffraction (XRD) patterns shown in Figure 1(a, b). All peaks were indexed by x-MnO2 (ICSD: 44–141). The refined lattice constants are a = b = 0.9840 nm, c = 0.2856 nm for MnO2-110, and a = b = 0.9871 nm, c = 0.2845 nm for MnO2-210, respectively. Compared with the reported lattice parameters of x-MnO2, a = b = 0.9785 nm and c = 0.2863 nm (ICSD: 44–141), the lattice expansion in the [h k 0] directions is due to the loosened lattice constraints in the nanostructures. On the other hand, the [0 0 l] constant decreases slightly. These two samples have obvious differences in preferred growth orientation, as judged from the intensity of the diffraction peaks. The refinement also indicates slight orientations along the [3 0 0] and [1 0 0] directions in both samples. The orientation also comes from the high aspect ratio of their nanowire structures. The nanowires lie on the substrates during XRD measurements. All samples exhibit sharp diffraction peaks, indicating their highly crystalline nature, which is consistent with the high resolution transmission electron microscope (HRTEM) observations.

Microstructures of the MnO2-110 were observed by scanning electron microscopy (SEM) and by transmission electron microscopy (TEM), as shown in Figure 1(c). The morphology of the sample with (1 1 0) planes exposed consists of ultra-long nanowires with width of 30 nm and length of more than 10 μm, as shown in the inset of the SEM image. The HRTEM images and the selected area electron diffraction (SAED) pattern indicate that the x-MnO2 nanowires have (1 1 0) planes exposed on the side walls, which is in agreement with the XRD refinement results. MnO2-210 has nanowires with a rectangular morphology, with width of ~20 nm and length of ~1 μm, based on SEM and TEM observations (Figure 1(d)). The HRTEM images and the SAED pattern indicate that the x-MnO2 nanowires have (2 1 0) planes exposed on the side walls, which is in agreement with the XRD refinement results. The HRTEM images of the surface of a single nanowire reveal the highly crystalline nature of the x-MnO2 nanowires. The different growth speeds of the different planes and the electronic structure are responsible for this structural variation. It should be noted that the tetragonal crystal structure (with space group I 4/m) of x-MnO2 shows different preferred growth directions in different reaction environments.

The surface sensitive X-ray photoelectron spectroscopy (XPS) technique was employed to examine the valence state of Mn ions in x-MnO2 nanowires. The survey scan indicates both MnO2-110 and MnO2-210 are high impurity samples, as shown in Figure S1. The resulting high resolution scans of Mn-2p1/2 and Mn-2p3/2 were fitted with four Gaussian-Lorentz peaks, p1–p4, respectively, as shown in Figure 1(e, f), where p1 and p2 are responsible for the observed 2p1/2 peak of Mn2+, and p3 and p4 for the 2p3/2 peak. For MnO2-110, the binding energies of p1 and p3 are 653.78 and 642.41 eV, respectively, which can be attributed to the loose surface structure around the MnO6 octahedra. The binding energies of p2 and p4 are 654.65 and 642.76 eV, respectively, which are attributed to the body MnO6 octahedra. These two different states are present in the ratio of ~1.9 : 1 in the detected depth of the sample. Similarly, for MnO2-210, the binding energies of p1 and p3 are 653.79 and 642.26 eV, while for p2 and p4, they are 654.85 and 643.60 eV, respectively. The two different states are present in the ratio of ~1.4 : 1 in the detectable depth of XPS. Thus, it is concluded that the amount of surface MnO6 octahedra in MnO2-110 is higher than in MnO2-210 due to the rougher surface. The lower oxidation states of Mn, such as Mn2+ and Mn3+, were not detected, or their contents were below the detectable limits of XPS, in both MnO2-110 and MnO2-210.

Magnetic properties. x-MnO2 has been reported as an antiferromagnetic substance with a Néel temperature (T_N) of ~24.5 K24. Both zero-field-cooled (ZFC) and field-cooled (FC) susceptibility were measured under a 100 Oe magnetic field, and the results are shown in Figure 2(a). The ZFC curve bifurcates from the FC one below ~13 K and shows a peak at ~13 K for both samples. The bifurcation indicates that the magnetic phase is making a transition from paramagnetism (PM) to a spin-glass-like state in the x-MnO2 nanowires25, which is similar to the previously reported transition temperature in x-MnO2 nanowires25. The spin-glass moments are easily polarized under low magnetic field, while the AFM susceptibilities are much lower. This means that the characteristic of the AFM transition is almost buried in the ferromagnetic cluster ordering. Careful observation can also find the weak AFM transition feature in MnO2-110 between 20 and 30 K. The high temperature susceptibility data for x-MnO2 are in good agreement with the Curie–Weiss law and therefore can be fitted to the equation 1/\(\chi(T) = (T - \theta)/C\), where \(\theta\) is the Curie–Weiss temperature, and C is the Curie–Weiss constant. The fitted result is presented in the inset of Figure 2(a). The 1/\(\chi(T)\) of MnO2-110 was fitted with...
antiferromagnetic part with \( \theta = -621 \) K and \( C = 2.608 \) emu-K/Oe-mol with contribution of 98.3% and ferromagnetic part with \( \theta = -33.7 \) K and \( C = 5.216 \) emu-K/Oe-mol with contribution of 1.7%. The parameters are \( \theta = -166 \) K and \( C = 1.816 \) emu-K/Oe-mol for MnO\(_2\)-210, respectively. The negative \( \theta \) value indicates the antiferromagnetic behaviour of the \( \alpha \)-MnO\(_2\) nanowires. The \( \theta \) value of MnO\(_2\)-110 is much lower than that of MnO\(_2\)-210, implying a much stronger antiferromagnetic coupling in MnO\(_2\)-110. The susceptibility values of MnO\(_2\)-210 increase gradually with cooling temperature and do not show sudden transition at \( T_N \). In contrast, the transition of MnO\(_2\)-110 shows intensive susceptibility variation and its absolute susceptibility values are lower than those of MnO\(_2\)-210 when the temperature is higher than \( \sim 20 \) K. Furthermore, the temperature dependence of susceptibility is quite weak compared

Figure 1 | Phase, microstructure, and valence state. (a), Indexed XRD pattern with refinement results of MnO\(_2\)-110 (refined with Rietica, weighted profile R-factor, \( R_{wp} \): 13.50). (b), Indexed XRD pattern of MnO\(_2\)-210 (refined with Rietica, \( R_{wp} \): 12.80). The insets show the square tunnel structure of \( \alpha \)-MnO\(_2\) with space group \( I4/m \). The (1 1 0) and (2 1 0) planes are highlighted by the green shaded areas, respectively. (c), Microstructural observation results for MnO\(_2\)-110: SEM image with inset to show the ultra-long nature of the nanowires, TEM image, TEM image of surface for a single nanowire, and HRTEM image of surface for a single nanowire with inset SAED pattern. (d), Microstructural observation results for MnO\(_2\)-210: SEM image, TEM image, TEM image of surface for a single nanowire, and HRTEM image of surface for a single nanowire with inset SAED pattern. The HRTEM images of the surface and the SAED patterns (c), (d) indicate that the \( \alpha \)-MnO\(_2\) nanowires have exposed (1 1 0) planes and (2 1 0) planes, respectively. (e), (f), X-ray photoelectron spectra of Mn 2p in \( \alpha \)-MnO\(_2\) nanowires: MnO\(_2\)-110 (e) and MnO\(_2\)-210 (f). Fitted peaks p1 and p2 are responsible for the observed 2p\(_{1/2}\) peak of Mn\(^{4+}\), and fitted peaks p3 and p4 for the 2p\(_{3/2}\) peak.
with that of \( \text{MnO}_2 \) in the high temperature region. Interestingly, the \( T_N \) values in the two samples are similar. This can be understood that the coupling of the majority of the inside atoms in both samples is antiferromagnetic - resembling the case in bulk \( \text{MnO}_2 \). Nevertheless, the distinct surface magnetic ground states of (2 1 0) and (1 1 0) show great influences on the Curie-Weiss Temperatures.

The 5 K hysteresis loops of \( \text{MnO}_2 \)-110 after ZFC or FC under 10 kOe magnetic field from 350 down to 5 K are presented in Figure 2(b), with measurements between \( \pm 70 \) kOe. Both the ZFC and FC loops deviate from antiferromagnetism under magnetic field, showing high remnant magnetism and a strong coercive field, as shown in the upper left inset of Figure 2(b). This provides evidence of a mixed state of a component from the antiferromagnetic core of \( \text{MnO}_2 \) combined with stable net surface spins. The high remnant magnetism indicates the great amount of net magnetic spin on the surface, and the strong coercive field indicates anisotropic magnetic coupling. The hysteresis loops are not saturated under \( \pm 70 \) kOe due to the contribution of the antiferromagnetic core as well as the spin-glass component, which is a common phenomenon in the case of nanocrystalline compounds, alloys, and oxide materials\(^{27,28}\). The open loop, as shown in the lower right inset of Figure 2(b), is a characteristic of spin-glass\(^{27,28}\), with slow dynamics. The positive maximum magnetization \( M_{EB}^+ \) and the negative maximum magnetization \( M_{EB}^- \) under \( \pm 70 \) kOe show symmetric behaviour with a very small difference below 0.019 emu/g, which is defined as the magnetization exchange bias: \( M_{EB} = (M_{max} + M_{max})/2 \). Exchange bias behaviour is a quite normal phenomenon in nanoparticles with size/surface induced ferromagnetic clusters. The magnitude of the exchange bias effect is usually compared quantitatively, using the following two fields, the exchange bias field, \( H_{EB} \), and the coercive field, \( H_C \), defined as \( H_C = |H_{C1} - H_{C2}|/2 \) and \( H_{EB} = (H_{C1} + H_{C2})/2 \), where \( H_{C1} \) and \( H_{C2} \) are the left and right coercive fields, respectively. The \( H_C \) of \( \text{MnO}_2 \)-110 approaches 3667 Oe, while the \( H_{EB} \) is only \( \sim -50 \) Oe.

Figure 2(c) shows the hysteresis loops of \( \text{MnO}_2 \)-210. The loops deviate slightly from linear behaviour. Both the remnant magnetism and the coercive field are quite weak compared with those of \( \text{MnO}_2 \)-110, as shown in the upper left inset of Figure 2(c). Obvious exchange bias behaviour was observed in the FC loop, but is absent from the ZFC loop. \( H_{max} \) the maximum applied magnetic field, is crucial for investigating the exchange bias effect, because small \( H_{max} \) may lead to the displacement of the magnetic hysteresis loop, even for FM and glassy magnetic substances. This is attributed to the irreversible magnetization processes known as minor loop effects\(^{29}\). When \( H_{max} \) is small, the FC hysteresis loops are always shifted towards the negative field and positive magnetization. The \( M_{EB} \) value is very small (less than 0.018 emu/g) in the \( M(H) \) loop. Thus, the exchange bias effect is indeed present in the \( \alpha \)-\( \text{MnO}_2 \).
nanowires. The $H_C$ of MnO$_2$-110 is $\sim 154$ Oe, and the $H_{EB}$ is $\sim -451$ Oe. The exchange bias effect is much stronger in MnO$_2$-210 than in MnO$_2$-110.

Comparing the magnetization behaviour of MnO$_2$-110 and MnO$_2$-210, it is found that the former sample shows much stronger and more stable net magnetic coupling, as shown in Figure 2(d), but does not display strong exchange bias behaviour. The difference is attributed to their surface structures: the (1 1 0) plane contains chains of MnO$_6$ octahedra on the smooth matrix of (2 1 0) tunnels, while the (2 1 0) plane forms a step-type surface with chains of MnO$_6$ octahedra. The higher density of MnO$_6$ octahedral chains in MnO$_2$-110 is responsible for its strong magnetization. On the other hand, the weak coupling between the core AFM spins and the surface spins cannot generate an intensive exchange bias when the magnetic field is reversed. In MnO$_2$-210, the core AFM spins couple intensively to the weak surface spins during the magnetic field reversal, which is the origin of the exchange bias behavior.

Owing to their inherent shape anisotropy and the ability to incorporate different components, magnetic nanowires (MNWs) offer unique magnetic properties distinct from those of bulk, thin films, and particles. A key property of MNWs lies in the strong coupling of magnetic properties with the nanowire orientations. For practical applications, it is desirable to synthesize nanowires with tuneable magnetic ordering, as they can offer greater flexibility in the design and optimization of nanodevices. Bulk $\alpha$-MnO$_2$ has a Hollandite-type structure (tetragonal; space group 14/m; $a = 9.777$ Å and $c = 2.855$ Å). This tunnel-structured oxide is characterized by double chains of edge-sharing MnO$_6$ octahedra, which are linked at corners to form one-dimensional (1D) (2 × 2) and (1 × 1) tunnels that extend in a direction parallel to the c-axis of the tetragonal unit cell (Figure 3(a)). According to Néel’s model, neighboring pairs of octahedrally coordinated Mn$^{4+}$ (d$^5$, S = 3/2) ions are aligned antiparallel to each other (Figure 3(b)), leading to an antiferromagnetic ground state (see Figure 3(c) and Supplementary Figure S2).

To confirm the influence of the surface on the magnetism, density functional theory (DFT) calculations were performed to distinguish the magnetism of bulk $\alpha$-MnO$_2$ from those of exposed (1 1 0) and (2 1 0) surfaces. Bulk $\alpha$-MnO$_2$ possesses an antiferromagnetic ordering between the corner-sharing MnO$_6$ octahedra and a ferromagnetic ordering between the edge-sharing MnO$_6$ octahedra, as shown in Figure 3(c) and Supplementary Figure S2. The corresponding ferromagnetic structure is only 12 meV per cell higher in energy. The magnetic moments of Mn$^{4+}$ and O$^{2-}$ are $\pm 2.79$ $\mu_B$ and $\sim \pm 0.1$ $\mu_B$, respectively. These values are in excellent agreement with the 3 $\mu_B$ per Mn based on crystal field theory.

We used supercells containing symmetric slabs with inversion symmetry to simulate the MnO$_2$-110 and MnO$_2$-210 surfaces. For MnO$_2$-110, we considered the stoichiometric O-terminated (96 atoms) and non-stoichiometric Mn-terminated (92 atoms) surfaces, denoted as (1 1 0)-O and (1 1 0)-Mn, respectively. For MnO$_2$-210, we only considered the stoichiometric cell, containing 96 atoms. For each surface, to obtain the ground-state magnetic structure, various possible magnetic alignments for the surface or subsurface layers have been considered and compared. The calculated spin-density isosurface plots for the bulk (shown in a 2 × 2 × 2 cell) and the plots for (1 1 0)-O, (1 1 0)-Mn, and MnO$_2$-(2 1 0) are shown in Figure 3(d–f), respectively. For the (1 1 0)-O, in the ground magnetic state, the Mn surface layer and the first subsurface layer are coupled ferromagnetically (Figure 3(d)). The Mn magnetic moments are 2.94 $\mu_B$ and 2.88 $\mu_B$. For the (1 1 0)-Mn (Figure 3(e)), which involves strong structural distortion of the surface atoms, in the ground state, only the surface Mn layer is coupled ferromagnetically, with the Mn atomic moment being 4.01 $\mu_B$, suggesting Mn$^{4+}$ ions. The Mn moments in the subsurface layer are 2.75 $\mu_B$, close to the moment in the bulk, 2.80 $\mu_B$. Considering the absence of the Mn$^{3+}$ state in the
Tuneable electronic bandgap energy. MnO$_2$ has been demonstrated to be a highly efficient photocatalyst$^{37}$, either alone or in MnO$_2$/TiO$_2$ heterogeneous photocatalysts$^{38,39}$. Figure 4(a) shows the ultraviolet-visible (UV-vis) absorption spectrum of the $\alpha$-MnO$_2$ nanowires. Broad absorption bands ranging between 300 and 600 nm with peak positions of $\sim$400 nm for MnO$_2$-210 and $\sim$450 nm for MnO$_2$-110 are observed. The $d^3d$ transitions of Mn ions in the $\alpha$-MnO$_2$ nanowires are responsible for the absorption in the visible light range. The Mn 3$d^3$ energy level splits into lower ($t_{2g}$) and higher ($e_g$) energy levels in the ligand field of MnO$_6$ octahedra, and the energy difference between the $e_g$ and $t_{2g}$ states is responsible for the optical bandgap energy$^{40}$. The bandgap energy $E_g$ for the $\alpha$-MnO$_2$ nanowires was estimated using the Kubelka-Munk function to plot the product of the square root of the absorption coefficient and the photon energy against the incident photon energy ($hv$)$^{41}$. A straight line in a photon energy range close to the absorption threshold can be fitted, as shown in the inset of Figure 4(a). $\alpha$-MnO$_2$ nanowires have an indirect electronic transition near the bandgap$^{40,42}$. The bandgap energy for the $\alpha$-MnO$_2$ nanowires can be derived as 0.98 eV for the sample with the exposed (1 1 0) planes, while it is 0.84 eV for the sample with exposed (2 1 0) planes, as derived from the intercept of the linear portion with the axis. Remarkable differences in the optical properties of nanostructured MnO$_2$ materials were previously observed. For example, Pereira et al. found that the absorption of MnO$_2$ colloidal at longer wavelengths strongly decreases as the MnO$_2$ particles become smaller$^{43}$. Gao et al. observed a bandgap of 1.32 eV in MnO$_2$ nanofibers with typical diameters of 20–60 nm and lengths of 1–6 pm$^{44}$. Sakai et al. also reported that MnO$_2$ nanosheets with a very small thickness of about 0.5 nm had bandgap energy of about 2.23 eV$^{45}$. The shift in the bandgap to higher energies can be attributed to the carrier confinement in the small semiconductor particles. Figure 4(b) is a sketch of the possible bandgap alignment of MnO$_2$. Selective surface engineering can be an effective tool to control the driving force of charge transport and charge separation.

Electrochemical properties. Lithium storage properties of the $\alpha$-MnO$_2$ nanowires were investigated using the galvanostatic charge–discharge method. The capacity difference between the two samples is obvious, as shown in Figure 5(a). The origin of the performance variation in $\alpha$-MnO$_2$ nanowires can be attributed to the different intercalation(absorption behavior of lithium ions as they interact with exposed (1 1 0) and (2 1 0) surfaces, as illustrated in Figure 5(b). The capacity of the batteries depends on the intercalation Li$^+$ ions in $\alpha$-MnO$_2$ lattice under the charge/discharge voltage. One of the determinant factors is the penetration ability of Li$^+$ ions in the electrolyte through the close-packed plane of MnO$_6$ into the (2 $\times$ 2) tunnels. The more the (2 $\times$ 2) tunnels exposed to electrolyte, the more chance for the Li$^+$ ions intercalate into the $\alpha$-MnO$_2$ lattice. Judging from the theoretical period structure of outermost layers of exposed with (1 1 0) and (2 1 0) plane as demonstrated in Figure S5, the (2 $\times$ 2) tunnels have more chance to accept Li$^+$ ions to build up the capacity of the material. The MnO$_6$ as blockers on the (1 1 0) and (2 1 0) surfaces were highlighted in Figure S5 to demonstrate the intercalation chance for Li$^+$ into the (2 $\times$ 2) tunnels. It can be roughly estimated that direct exposure rate of the (2 $\times$ 2) tunnels to electrolyte is 2/3 when the (1 1 0) plane was the exposed facet. The rate increased to 4/5 for (2 1 0) plane as the exposed facet. This may be one of the reasons that the capacity of MnO$_2$-210 is double that of MnO$_2$-110.

In summary, the evidences of facet of nano particles suggest the facet control of nano materials for practical application is essential for the exploration of high performance. The magnetic property dependence on exposed crystal plane of $\alpha$-MnO$_2$ nanowires reveals that the variation of the size and morphology dependence of...
nanomagnetism and electrochemical reaction should be examined to explain the origin of the performance difference and maximize the performance through facet control engineering.

**Methods**

**Synthesis of MnO$_2$-110.** To synthesize $\gamma$-MnO$_2$ nanowires with different exposed planes, two different hydrothermal reaction processes were employed in Teflon-lined autoclaves. Rectangular MnO$_2$-110 was synthesized by a hydrothermal method with procedures reported in Wang et al.’s$^4$ and Gao et al.’s work$^5$. KMnO$_4$ (Aldrich, 99.0%) and NH$_4$F (Aldrich, 99.9%) were used to form $\gamma$-MnO$_2$ under neutral hydrothermal conditions. In a typical procedure, KMnO$_4$ (0.001 mol) and NH$_4$F (0.001 mol) were dissolved under magnetic stirring in 40 mL doubly deionized water to form a clear solution. The solution was transferred into a 50 mL autoclave with a Teflon liner. The autoclave was sealed and maintained at 150 °C for 24 h, and then cooled to room temperature naturally. The suspension was then alternately centrifuged with doubly deionized water and ethanol several times, and the resulting brown precipitate was dried in an oven at 80 °C for 10 h.

**Synthesis of MnO$_2$-210.** Rectangular MnO$_2$-210 was synthesized with a Mn$^{2+}$ source: Mn$^{2+}$ + (NH$_4$)$_2$SO$_4$ + 2H$_2$O $\rightarrow$ MnO$_2$ + (NH$_4$)$_2$SO$_4$ + 2H$_2$SO$_4$. H$_2$SO$_4$ was added to the solution to adjust its pH value, since the size and morphology of the nanostructures show a strong dependence on the pH value of the formation environment$^6$. In a typical synthesis, MnCO$_3$ (Aldrich, 99.9%), (NH$_4$)$_2$SO$_4$ (Aldrich, >98%), HNO$_3$ (>98%), and H$_2$SO$_4$ (Aldrich, 95–98%) were used as received without further purification. MnCO$_3$ (0.02 mol) was dispersed in deionized water (200 mL), and HNO$_3$ (0.04 mol) was then added to make a transparent solution. Then, (NH$_4$)$_2$SO$_4$ (0.02 mol) was added, and the solution was diluted to 300 mL. After the addition was completely dissolved, concentrated H$_2$SO$_4$ (20 mL) was added, and the solution was diluted to 400 mL and stirred for 30 min. The hydrothermal treatment was performed in a Teflon-lined autoclave, with heating at 140 °C for 1 h in a microwave device. After the reaction was completed, the solution cooled to room temperature, and the resulting suspension was centrifuged in order to separate the precipitate from the supernatant liquid. The precipitate was washed and centrifuged two times and then dried at 80 °C overnight.

**Physical characterization.** Both samples were microstructurally characterized by X-ray diffraction (XRD-GBCMMA, Cu K$_{α1}$, $\lambda = 0.154056$ nm) in conjunction with Rietveld refinement (Rietica), UV-Visible spectrophotometer (Cary 5000 UV-Vis, Agilent), X-ray photoelectron spectroscopy (XPS: Escalab 220-iXL, Al K$_{α}$), field emission gun scanning electron microscopy (FEG-SEM: JSM-6700F), and transmission electron microscopy (TEM: JEOl-2010) with high resolution TEM (HRTEM), operating at 200 kV. Selected area electron diffraction (SAED) patterns were also collected for crystal structure analysis. Magnetic properties were measured using a commercial vibrating sample magnetometer (VSM) model magnetic properties measurement system (MPMS: Quantum Design, 14 T) in applied magnetic fields up to 70 kOe. The nanoparticles were filled into a polypropylene powder holder, which is an injection moulded plastic part as powder container during the VSM measurement process. The polypropylene powder holder was mounted into a brass trough, which is made from cartridge brass tubing with a cobalt-hardened gold plating finish. Both polypropylene powder holder and brass trough were made by Quantum Design as commercial VSM sample holders with very low magnetic moments, which are much lower than the moments of $\gamma$-MnO$_2$ samples.

**Electrochemical characterisation.** Electrochemical characterisation of MnO$_2$-110 and MnO$_2$-210 was conducted in 2032-type coin cells. The working electrodes were prepared by mixing 80 wt% $\gamma$-MnO$_2$ nanowires and 10 wt% carbon black, along with 10 wt% polyvinylidene difluoride (PVDF), in the presence of N-methyl pyrrolidinone (NMP), and this slurry was spread on aluminium foil and then heat-treated at 80 °C under vacuum overnight. CR2032 coin type cells were employed in the battery testing, with lithium foil serving as counter electrode and a porous Celgard polypropylene membrane as separator. The electrolyte consisted of a solution of 1.0 M LiPF$_6$ dissolved in a mixture of the solvents ethylene carbonate and dimethyl carbonate in a volume ratio of 1:1. Galvanostatic charge–discharge measurements were performed over the potential range from 2 V to 4.5 V (vs. Li/Li$^{+}$) at a constant current density of 20 mA g$^{-1}$ on a LandCT2001A battery tester.

First principles simulation. All calculations were performed using spin-polarised DFT with the generalized gradient approximation$^7$ (GGA) for the exchange-correlation functional, as implemented in the all-electron DMol$^3$ code$^8$. Earlier study shows that GGA functional predict the correct ground magnetic states for a range of Manganese-oxides$^9$. The wave functions are expanded in terms of a double numerical quality localized basis set with a real-space cut-off of 10 bohr. For bulk calculations, the Brillouin zone (BZ) integration was performed using Monkhorst-Pack grids of 12 × 12 × 36 was used. The calculated antiferromagnetic $\gamma$-MnO$_2$ lattice constants are $a = b = 9.731$ Å and $c = 2.854$ Å, which compare well with the experimental ones. For surface supercells, a 30–40 vacuum region is used between adjacent slabs. All surfaces are fully relaxed, while keeping the innermost three centre layers fixed at the bulk values. The Brillouin zone (BZ) integration was performed using Monkhorst-Pack grids of 8 × 8 × 1, with 18 k points in the irreducible part of the BZ for all the surfaces. The convergence criteria for the forces on the atoms are less than 0.01 eV Å$^{-1}$, and for the total energy 0.05 meV.

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Author contributions

W.X.L. designed the study, with advice from S.X.D. and Z.Q.S. The initial synthesis was performed by W.X.L., R.Z. and W.X.L. obtained the X-ray diffraction data, and microstructural observation and electron diffraction patterns were obtained by W.X.L. and Z.Q.S. Rietveld refinements were initially performed by W.X.L. and XPS were measured and analyzed by Z.Q.S. Magnetic susceptibility was measured and analyzed by R.Z. and W.X.L. The semiconducting properties and lithium battery performances were measured by G.D.D. The density functional theory calculations were performed by X.Y.C. All authors discussed the results: W.X.L. and Z.Q.S. wrote and revised the manuscript, with discussions mainly with X.Y.C., R.K.Z., S.X.D. and S.P.R.

Additional information

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