Supporting information

P-doped in situ induced Se vacancy enhances the supercapacitor performance of NiCo$_2$Se$_4$

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SEM images of NiCo$_2$Se$_x$-P$_{0.5}$ and NiCo$_2$Se$_x$-P$_2$ are shown in Fig. S1(a-b). After the phosphating treatment, both NiCo$_2$Se$_x$-P$_{0.5}$ and NiCo$_2$Se$_x$-P$_2$ showed a microsphere morphology with an average size of 5 μm, and the spherical surface was covered with a large number of nanoparticles. The low-magnification TEM images of NiCo$_2$Se$_x$-P$_{0.5}$ and NiCo$_2$Se$_x$-P$_2$ are shown in Fig. S1(c-f), and their size is about 5 μm, which is in agreement with the SEM results. Compared with NiCo$_2$Se$_x$-P$_1$ material, they are all microspheres, but further observation can be found that the surface of NiCo$_2$Se$_x$-P$_1$ material is needle-like, which may be that the amount of phosphorus doping will have some effect on its morphology, resulting in differences in the surface structure of the material. As for NiCo$_2$Se$_x$-P$_1$, the mesh structure formed by interconnecting neighboring nano-needles on its surface has abundant pores, and this multi-channel structure can accelerate the rapid penetration of electrolyte ions in the active material. Therefore, the electrochemical performance of NiCo$_2$Se$_x$-P$_1$ obtained after phosphorization treatment are better than the other two samples. Based on this we consider NiCo$_2$Se$_x$-P$_1$ as a typical sample for research.
Fig. S2 (a) N$_2$ adsorption/desorption isotherm, (b) Pore size distribution.

Fig. S3 XRD pattern of NiCo precursor.
**Fig. S4** XRD comparison of (210) and (211) crystal planes of Pure-NiCo$_2$Se$_4$ and NiCo$_2$Se$_x$-P$_1$.

**Fig. S5** DOS diagrams of Pure-NiCo$_2$Se$_4$, NiCo$_2$Se$_4$-P, NiCo$_2$Se$_x$ and NiCo$_2$Se$_x$-P.
Fig. S6 (a) Comparison of CV curves of AC electrode and NiCo$_2$Se$_x$P$_1$ electrode at 50 mV s$^{-1}$ scan rate, (b) CV curves of different voltage windows at NiCo$_2$Se$_x$P$_1$/AC scan rate of 50 mV s$^{-1}$.

Table S1 Performance comparison of NiCo$_2$Se$_x$P$_1$/AC devices with recently reported hybrid supercapacitors

<table>
<thead>
<tr>
<th>Supercapacitor device</th>
<th>Energy density (Wh kg$^{-1}$)</th>
<th>Power density (W kg$^{-1}$)</th>
<th>Reference</th>
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<tbody>
<tr>
<td>CoNi$_2$S$_4$/Bi$_2$O$_3$</td>
<td>86.6</td>
<td>1600</td>
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<tr>
<td>Ni$_2$Co$_3$Se$_4$/HPC</td>
<td>34.8</td>
<td>399.9</td>
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<tr>
<td>NiCo$_2$Se$_4$/rGO/TRGO</td>
<td>37.83</td>
<td>1433.55</td>
<td>3</td>
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<tr>
<td>(Ni$<em>{0.33}$Co$</em>{0.67}$)Se$_2$ CHSs//AC</td>
<td>29.1</td>
<td>800</td>
<td>4</td>
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<tr>
<td>NiCo$_2$Se$_4$/AC</td>
<td>25</td>
<td>490</td>
<td>5</td>
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<tr>
<td>Ni$<em>{0.67}$Co$</em>{0.33}$Se//RGO</td>
<td>36.7</td>
<td>750</td>
<td>6</td>
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<tr>
<td>(Ni$<em>{0.5}$Co$</em>{0.5}$)$_{0.85}$Se//carbon</td>
<td>70.58</td>
<td>320.02</td>
<td>7</td>
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<tr>
<td>NiCo$_2$Se$_x$P$_1$/AC</td>
<td>94.61</td>
<td>799.92</td>
<td>This work</td>
</tr>
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</table>
References


