Claims

1. A method, comprising:

forming a lithium metal film on a current collector, wherein the current collector comprises copper and/or stainless steel; and

forming a protective film stack on the lithium metal film, comprising:

forming a first protective film on the lithium metal film, wherein the first protective film comprises a $Li_9Ti_5O_{12}$ film, and wherein forming the first protective film on the lithium metal film comprises depositing a $Li_4Ti_5O_{12}$ film on the lithium metal film, and forming the $Li_9Ti_5O_{12}$ film from the $Li_4Ti_5O_{12}$ film.

2. The method of claim 1, wherein forming the protective film stack on the lithium metal film further comprises forming a second protective film on the first protective film, the second protective film comprising a lithium transition metal dichalcogenide.

3. The method of claim 2, wherein the lithium transition metal dichalcogenide comprises a transition metal dichalcogenide having the formula MX_2, wherein M is selected from Ti, Mo, or W and X is selected from S, Se, or Te.

4. The method of claim 3, wherein the transition metal dichalcogenide is selected from TiS_2, MoS_2, WS_2, or a combination thereof.

5. The method of claim 1, wherein $Li_4Ti_5O_{12}$ film is deposited on the lithium metal film via a physical vapor deposition (PVD) process.

6. The method of claim 5, further comprising exposing the $Li_4Ti_5O_{12}$ film to a lithiation process to form the $Li_9Ti_5O_{12}$ film.

7. The method of claim 5, wherein the $Li_4Ti_5O_{12}$ film is reduced to form the $Li_9Ti_5O_{12}$ film.

8. The method of claim 2, wherein the lithium transition metal dichalcogenide is selected from lithium-titanium-disulfide, lithium-tungsten-disulfide, lithium-molybdenum-disulfide, or a combination thereof.

9. The method of claim 2, wherein forming the lithium transition metal dichalcogenide comprises:

depositing a TiS_2 film on the $Li_4Ti_5O_{12}$ film or the $Li_9Ti_5O_{12}$ film via a chemical vapor deposition process; and

exposing the TiS_2 film to a lithiation process to form a $LiTiS_2$ film on the $Li_4Ti_5O_{12}$ film or the $Li_9Ti_5O_{12}$ film.

10. The method of claim 9, wherein depositing the TiS_2 film on the $Li_4Ti_5O_{12}$ film or the $Li_9Ti_5O_{12}$ film comprises:

(a) flowing $TiCl_4$ into a processing region;

(b) purging the processing region;

(c) flowing H_2S into the processing region to form the TiS_2 film;

(d) purging the processing region; and

(e) repeating (a)-(d) until the TiS_2 film achieves a targeted thickness.

11. The method of claim 10, wherein the first protective film has a thickness of 100 nanometers or less.

12. The method of claim 11, wherein the second protective film has a thickness of 100 nanometers or less.

13. An anode electrode structure, comprising:

a current collector comprising copper and/or stainless steel;

a lithium metal film disposed directly on the current collector; and

a protective film stack disposed directly on the lithium metal film, comprising:

a first protective film disposed directly on the lithium metal film, the first protective film comprising $Li_9Ti_5O_{12}$; and

a second protective film disposed directly on the first protective film, the second protective film comprising a lithium transition metal dichalcogenide.

14. The anode electrode structure of claim 13, wherein the lithium transition metal dichalcogenide comprises titanium, molybdenum, or tungsten.

15. The anode electrode structure of claim 13, wherein the lithium transition metal dichalcogenide comprises a transition metal dichalcogenide having the formula MX_2, wherein M is selected from Ti, Mo, or W and X is selected from S, Se, or Te.

16. The anode electrode structure of claim 15, wherein the transition metal dichalcogenide is selected from TiS_2, MoS_2, WS_2, or a combination thereof.

17. The anode electrode structure of claim 16, wherein the first protective film has a thickness of 100 nanometers or less.

18. The anode electrode structure of claim 17, wherein the second protective film has a thickness of 100 nanometer or less.

19. An energy storage device, comprising:

the anode electrode structure of claim 13;

a cathode electrode structure; and

a solid electrolyte film formed between the anode electrode structure and the cathode electrode structure.

20. The energy storage device of claim 19, wherein the solid electrolyte film is comprised of one or more of: LiPON, doped variants of either crystalline or amorphous phases of $Li_7La_3Zr_2O_{12}$, doped anti-perovskite compositions, argyrodite compositions, lithium-sulfur-phosphorous materials, Li_2S-P_2S_5, $Li_{10}GeP_2S_{12}$, Li_3PS_4, lithium phosphate

glasses, (1-x)LiI–(x)Li_4SnS_4, xLiI–(1-x)Li_4SnS_4, crystalline LLZO, amorphous (1-x)LiI–(x)Li_4SnS_4 mixture, amorphous xLiI–(1-x)Li_4SnS_4, $Li_3S(BF_4)_{0.5}Cl_{0.5}$, $Li_4Ti_5O_{12}$, lithium doped lanthanum titanate (LATP), $Li_{(2+2x)}Zn_{(1-x)}GeO_4$, $LiTi_2(PO_4)_3$, $LiHf_2(PO_4)_3$, $LiGe_2(PO_4)_3$, or any combination thereof, and wherein x is between 0 and 1.