

Li_3PO_4) and an assist of nitrogen. The anode film **932** is a metal, e.g., copper, and is deposited by a first source of copper and a secondary source of an inert material, e.g., xenon. In another embodiment, the anode film includes carbon. In yet another embodiment, the anode is formed of pure lithium. In some embodiments, the anode is a lithium alloy. In some embodiments, the anode includes an oxide.

[0196] FIG. 9C shows a further embodiment of a thin-film energy-storage device **910C**. This device **910C** includes a seed layer **950** formed on the cathode contact **924**. Seed layer **950** is formed on the cathode contact **924** prior to forming the cathode film **927**, as described herein, on the seed layer **950** and substrate **920**. Seed layer **950** is formed using deposition techniques as described herein, e.g., physical vapor deposition such as arc source deposition. Seed layer **950** is a very thin, electrically conductive layer and has a small crystal size. The seed layer **950** also has a high sheet resistance and is non-reactive with the materials of adjacent films. In an embodiment, seed layer **950** has a thickness that is substantially thinner than the adjacent electrode film **927**. The material of the seed layer **950** is chosen such that the arriving adatoms of the subsequent material (e.g., in some embodiments, the material from the first source **311**, **511** or **711**) would have sufficient mobility to allow a period of activity once the adatom contacts the seed layer surface. This improves nucleation of the first few molecular layers of arriving material, minimizes strain associated with lattice mismatch and assists the arriving material to grow in a manner consistent with the desired crystal structure for cathode film **927**.

[0197] In some embodiments, a seed layer **955** is formed on the electrolyte layer **928** prior to forming anode film **932**, as described herein, on the seed layer **955**. Seed layer **955** improves nucleation of the first few molecular layers of arriving material, minimizes strain associated with lattice mismatch and assists the arriving material to grow in a manner consistent with the desired crystal structure for anode film **932**.

[0198] The ion transport properties of the materials used in the fabrication of energy-storage devices **910C**, e.g., rechargeable batteries, greatly influence the operation and quality of the device. For example, the total energy-storage capability of solid-state, lithium-ion batteries of a given area is limited by a depletion region that forms at or near the cathode/electrolyte interface. The depletion of this region and the inability for additional lithium ions to be transported out of the bulk of the cathode film **927** results in limited capacity and, thus, more frequent recharges. Additionally, the efficiency of the lithium ion transport through the electrolyte film **928** controls and dictates the maximum discharge rate that can be achieved for a given structure. The seed layer **950** improves the crystalline structure of the materials subsequently deposited, i.e., a cathode film **927** or an anode film. The growth of the first few atomic layers of a material significantly impacts its overall structure even when the final film is very thick relative to the initial few atomic layers. If the "seed" material is chosen such that the surface energy kinetics are conducive to pseudo-epitaxial growth of the subsequent material, high quality cathode and anode (electrode) films **927** and **932** are achieved. Examples of materials for seed layer **950** include chromium, chromium nitride, tantalum, tantalum nitride, tungsten, tungsten nitride, ruthenium and ruthenium nitride.

[0199] The thin-film energy-storage device fabricated according to the present teachings stores electrical energy by introducing ions into a storage layer and removing the ions from the storage layer to create an electrical potential at the contacts. In one embodiment, lithium ions are stored in an anode formed of a lithium-intercalation material with the battery in a charged state. In some embodiments, the anode is formed of a metal or a carbonaceous material. The lithium ions travel from the anode through the electrolyte layer to a cathode, which is also formed of a lithium-intercalation material, to discharge electrical energy from the battery. In order to achieve sufficient energy density to operate external circuitry, the lithium-intercalation material cathode and anode must intercalate (i.e., add) and de-intercalate (i.e., remove) of a substantial mole fraction of lithium ions. It has been found that the choice of intercalation material and fabrication techniques for the cathode determine many operating parameters of a solid-state, thin-film battery. The operating parameters include, but are not limited to, operating voltage range, capacity, specific power, and specific energy. One method of measuring the transport properties of ions in a battery is diffusivity, which is measured by a diffusion coefficient. The diffusion coefficient is a measure of how well a particular material allows ions to diffuse into and out of the material.

[0200] FIG. 10 shows comparative data for LiCoO_2 cathode films in the form of X-ray diffraction spectra. The LiCoO_2 cathode films were created according to the teachings herein and according to a control process that did not include a secondary source assist. A first source supplied a LiCoO_2 material using an electron-beam evaporation process. An assist, second source provided energy in the form of oxygen ions impinging at the location on the substrate whereat it is desired to grow a thin electrode (cathode) film from the LiCoO_2 first material. The beam of oxygen ions from the second source is not co-incident with the LiCoO_2 material from the first source. Four samples of LiCoO_2 thin films were grown according to the data in Table I.

TABLE I

Deposition Parameters	Film a	Film b	Film c	Film d
Electron beam power* (W)	500	500	500	500
Total gas flow, O_2 + Ar, (sccm)	0	10.8	10.8	10.8
O_2 gas ratio, $\text{O}_2/(\text{O}_2 + \text{Ar})$, (%)	NA	0.48	0.48	0.48
Chamber pressure (Torr)	9.2×10^{-7}	2.6×10^{-6}	3.7×10^{-6}	5.0×10^{-6}
Ion source power (W)	0	123	128	135
Ion source acceleration voltage (V)	0	41	64	135

[0201] The electron beam voltage for each first source used in forming films a-d is 5 kV with an emission current of 100 mA.

[0202] FIG. 10 shows that the LiCoO_2 films deposited with lower energy oxygen ions from the second source, samples "b" and "c", enhanced the formation of the desirable crystallite structure of the grown film relative to the non-assisted sample "a". Specifically, a more distinct (003) orientation of the crystal structure is found in ion-assisted samples "b" and "c" than in non-assisted sample "a". A strong (003) X-ray diffraction peak indicates one desired