Nanocrystalline 3D homojunctions for next generation opto-electronics

Planar *pn* junctions constitute an integral part of optoelectronic devices. Inorganic semiconductor crystals offer superior properties compared to organics but high-grade crystals are expensive and difficult to produce in large volume. Bulk heterojunction (BHJ) and ordered heterojunctions (OHJ) made of organic, inorganic or hybrid 3D nano junctions can mitigate the flexibility and scale-up challenges of 2D planar *pn* junctions. However, mismatched interfaces and low doping issues invariably limit the charge transfer processes in such artificially created 3D structures.

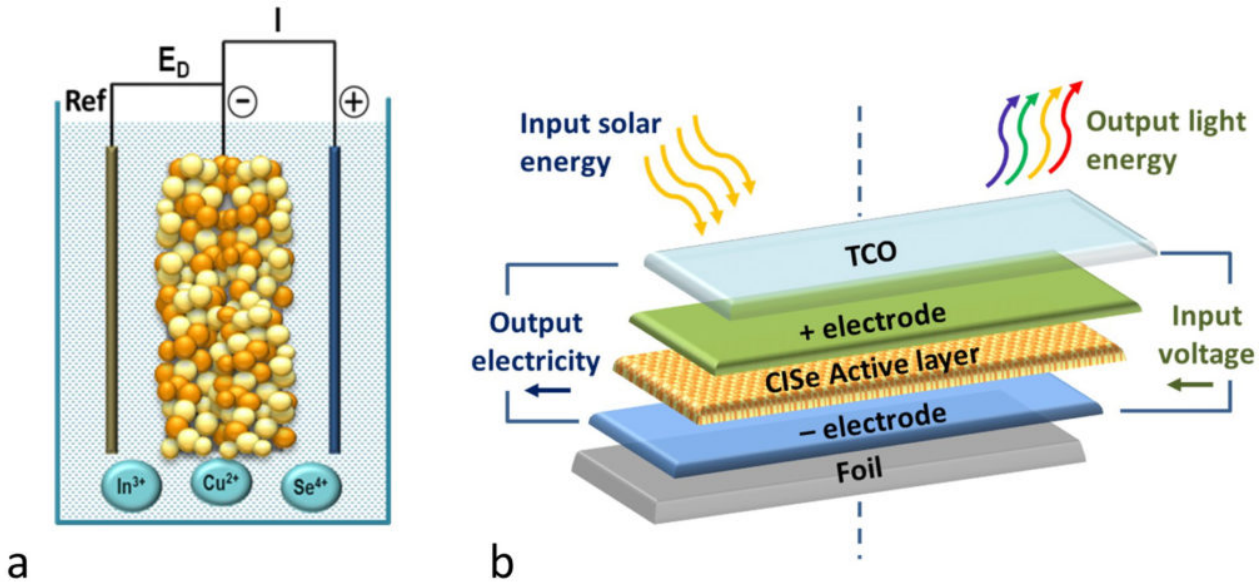

Fig. 1. Schematics of (a) SSE of pn NHJ film for creating (b) solar or lighting device.

We introduce a radically different and extremely low-cost route to naturally create high quality 3D *pn* junctions, exemplified here by two copper-indium-selenide (CISe) compounds. It entails single-step electrodeposition (SSE) of inherently ordered nanocrystalline homojunction (NHJ) CISe layer. The SSE process, followed by a brief air anneal creates an interconnected network of *p*-$CuInSe_2$ and *n*-$CuIn_3Se_5$ nanocrystals, Figure 1a. The CISe *pn* NHJs layer can be directly inserted between 2 electrodes to produce a device, Figure 1b. Furthermore, the 3D *pn* NHJ CISe layer is isotropic at the µm scale, allowing current flow in either direction. This ‘universal’ structure can serve as a solar cell to convert light to electricity, or as a light emitting diode to convert the applied voltage into light.

Besides proven performance and exceptional reliability, the CISe compounds offer self-stabilization, intrinsic doping and wide bandgaps. SSE exploits these attributes to create

homogeneous CISe *pn* NHJ films on large foil. The CISe NHJs exhibit unusual electro-optical attributes and quantum effects. Their spontaneous nanoscale ordering within the film facilitates interpenetration for fast, efficient generation, separation and transport of minority carriers; minimizes recombination and essentially performs the same functions as the high-end, planar *pn* junctions or OHJs, without their fabrication complexities. Surprisingly, CISe NHJ films exhibit quantized energy transitions, long lifetime, spectral range broadening and up-conversion, indicating that the CISe nanograins act as pure nanocrystals or quantum wells. Finely band-aligned contact materials can transform the CISe NHJ film into high performance 3rd generation devices.

Remarkably, the extraordinary CISe NHJs are generated by a very simple and practical non-vacuum SSE process. The *pn* CISe device can be mass produced in ambient atmosphere, using continuous roll-to-roll coating of device layers in successive steps, Figure 2. This production relevant tool offers small footprint, tolerates process variability and uses 99% materials with negligible waste. Thus SSE presents a viable pathway to simultaneously increase efficiency, reduce manufacturing cost and enable easy scale-up for a variety of flexible devices in simple thin-film form factor.

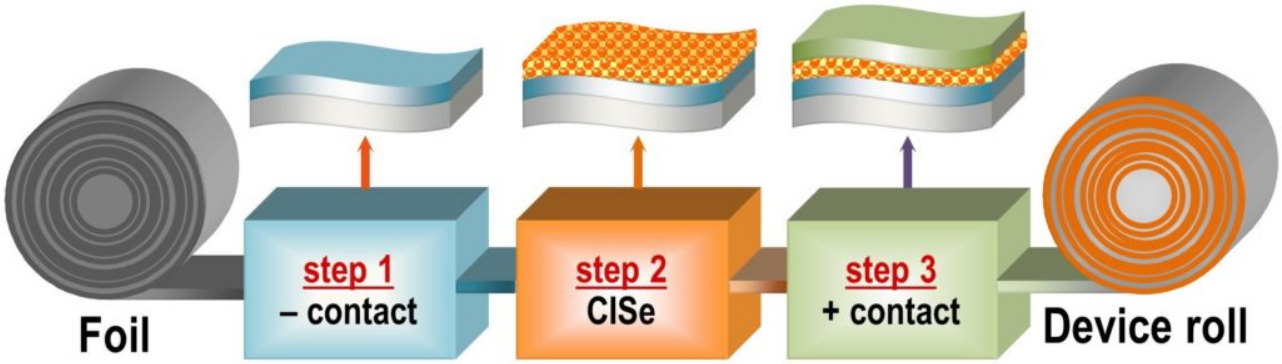

Fig. 2. Roll-to-roll fabrication for complete device.

Many unexpected features of SSE-made CISe films enable creating spin-off energy conversion technologies. The modular roll-to-roll system can be re-configured to create alternate device structures. The method may be adapted for other II-VI and III-VI chalcogenides. The resulting lightweight, flexible multi-component device roll can be fashioned into inexpensive flexible solar panels, or directly incorporated in solid state lighting devices, photoelectrodes and other energy conversion devices. Notably, the generally accessible SSE method presents a generic, very low-cost processing platform to create high quality CISe absorbers/emitters for direct use in alternate devices. This approach represents a significant advance in semiconductor processing.

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Publication

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