"Inherent Advantages of Crystalline Silicon for Large Scale Commercialization of Photovoltaics"

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November, 2009

Monocrystalline silicon is one of the best understood engineering materials in the world. The processing of monocrystalline silicon into electronic devices is the basis of a Trillion dollar plus industry world-wide. This industry is supported by a vast infrastructure of equipment manufacturers; material suppliers; universities; engineering firms; investment organizations and other entities, with a collective industrial experience of over 50 years, dating from the first practical silicon transistor in 1954 and fueled by explosive growth and investment after the invention of the first practical integrated circuit in 1958. The dominant material in this industry is monocrystalline silicon.

Photovoltaic cell manufacturing based on monocrystalline silicon leverages the direct relevance of much of the electronics industry's experience and infrastructure to the solar cell manufacturing process. For example, the monocrystalline substrate itself is essentially identical to the integrated circuit substrate in terms of raw material and crystal growth. This ensures that monocrystalline substrates (wafers) can be provided at high volume, with high and consistent quality and with predictable capital and processing costs and yields. Solar cells can then be made on those substrates with predictable, consistent high efficiency and yield.

This minimizes the scale-up risk for advanced monocrystalline silicon cell processing technology relative to the risks for "Second Generation" materials, because small batch, proof of concept crystalline technology demonstrations can be made on full-size substrates. This reduces the scale-up problem to one of replication, essentially an equipment and process engineering project taking full advantage of the infrastructures of both the photovoltaics industry and the larger electronics industry, and with the security of working on the world's best understood engineering material.

The problem of scale-up is substantially more difficult for second generation materials, which are in some cases poorly behaved (as in the case of the well-known Stabler-Wronski degradation phenomenon in amorphous silicon or the more common sensitivity to moisture exhibited by many thin film materials), but which are in all cases less well-developed than crystalline silicon in terms of the level of fundamental understanding of their material properties, of their process technologies and of the sophistication of their manufacturing infrastructure. The engineering problems involved in scaling up these thin film technologies are fundamentally more difficult.

Crystalline silicon is grown in bulk and its electronic properties are determined by the controlled addition of dopant atoms. Control of these growth and doping processes, which has taken decades to develop, is mature and effective. The most successful thin film materials to-date have been binary (CdTe) and quaternary (CIGS), defect-doped semiconductors. In these materials, their electronic properties are determined by the ratios of the component materials (slightly more or less Cd than Te for example). These materials can achieve high efficiency only though the control of material stoichiometry (the ratio of the two or four basic components) to sub-parts per million levels over the entire area of the device (whether the device is laboratory scale or a full-sized module). This makes the problem of scale-up not one of replication but truly one of scale because, once the engineering problem of manufacturing say a 10 cm square device is solved, the problem of making a device 100 square cm is substantially a new problem, like the difference between making concrete paving blocks for a garden walk and constructing an interstate highway. The concrete material may be more or less the same but the equipment and manufacturing techniques are vastly different. Then making a 1,000 square cm device is a new engineering problem yet again, one that requires new equipment of a different scale and level of sophistication and cost. These are difficult and costly development cycles which take time to get to market, similar to the multiple technical generations required to move silicon Czochralski ingot growth from 50 mm diameters to eventually 200 mm and then 300 mm. Since the mono-crystalline photovoltaic industry is comfortably based on 200 mm substrates, this issue of substrate uniformity at scale has already been solved.

This is not to say that thin films cannot be made in large areas, but rather that the problems of maintaining uniformity (and therefore high efficiency) over progressively larger areas have generally been understated and that therefore the gap between the performance of the best small area devices and those made in large scale is likely to remain large. In contrast, the gap between the best mono-crystalline laboratory devices and large scale manufacturing continues to shrink.

Moreover, for crystalline silicon the scale-up problem itself is largely one of purchasing more production lines and applying the plant engineering that takes advantage of volumetric economies of scale. This is again in contrast to the thin film problem of having to design the progressively larger and more complex equipment itself for materials and structures for which some of the fundamental physics and engineering are still being worked out, and for which long-term performance stability has yet to be demonstrated.

The result of this discrepancy in industrial and material maturity is that the nascent thin films will have a difficult time closing the performance gap of about a factor of two that exists between even the best thin film technologies and monocrystalline silicon at comparable manufacturing scale. Module conversion and balance of systems (BOS) costs per Watt will therefore continue to favor high efficiency crystalline silicon products, particularly since the module conversion costs per unit area tend to be higher for the thin film products (because of , among other things, their sensitivity to moisture). Industrial hygiene issues around the use of toxic heavy metals in the production processes for the present generation of thin films, and end of product life reclamation requirements due of the use of these same materials will also add cost and risk.

As the photovoltaic industry enters a period of what is likely to be explosive growth in the United States (and indeed in much of the world), the established stability, performance, scalability, low technical risk and rapid time to market of advance mono-crystalline silicon continue to support its market-leading position.