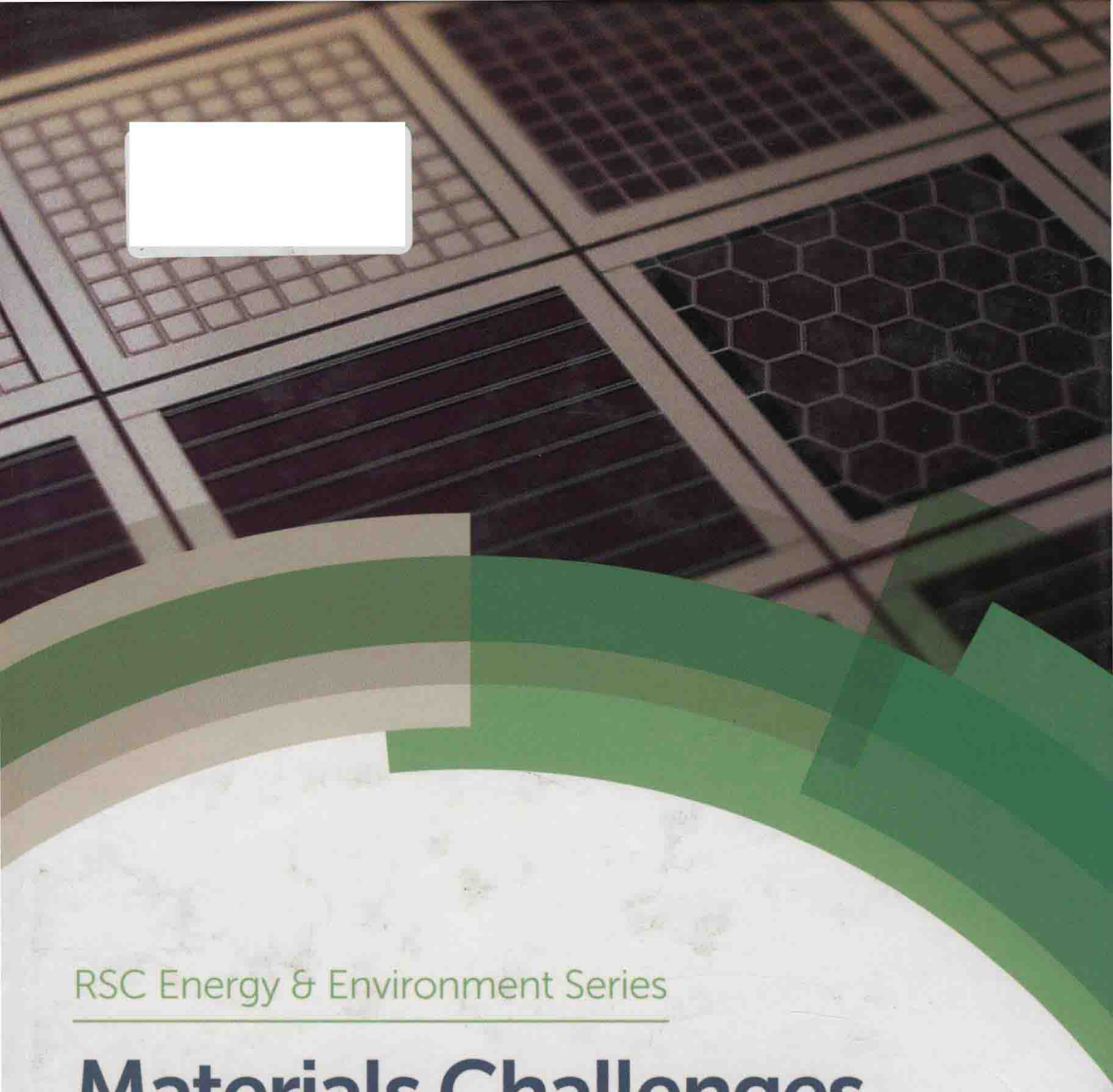

RSC Energy & Environment Series

Materials Challenges

Inorganic Photovoltaic Solar Energy

Edited by Stuart J C Irvine

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Materials Challenges

Inorganic Photovoltaic Solar Energy

Edited by

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Preface

This book provides an up-to-date account of exciting developments in thin film inorganic photovoltaic (PV) solar energy. For many years the thin film PV market was led by amorphous silicon and showed the potential for thin film products on glass substrates. This has grown rapidly over the past 10 years with new thin film PV materials going to large volume manufacture such as the polycrystalline thin film PV materials, cadmium telluride and copper indium diselenide. Amorphous silicon has also undergone a transformation with more stable and more efficient multi-junction cells.

The book is very timely because thin film PV is established in the market for large-scale solar energy production but is still small, and arguably in its infancy, compared with the predominant crystalline silicon PV module products. This has generated a wealth of research over the past 10 years to find solutions to challenges such as achieving higher conversion efficiency, greater long-term stability and reduction in manufacturing costs. The latter turns out to be important for materials research as some of the materials currently used in thin film PV might become in short supply in the future and are subject to commodity price fluctuations. For this reason the introduction, Chapter 1, includes an overview of techno-economic considerations that provide a context for the materials challenges covered in this book. The contents give an up-to-date summary of the latest research but also examine some of the fundamental considerations that underpin the technology. The fundamental considerations in thin film PV are covered in Chapter 2 and each of the remaining chapters develops different aspects of these underpinning considerations. The chapters on absorber materials (Chapters 3, 5, 6 and 7) cover materials systems from thin film silicon through to multi-junction III–V devices. There are also chapters common to assisting all the thin film PV materials systems meeting the challenges such as transparent conducting oxides, where in Chapter 4 we have an account of the pioneering

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work carried out at the US National Renewable Energy Laboratory (NREL) in Colorado, while in Chapters 8 and 9, the topics of light capture and photon management are covered. This makes a truly exciting combination of material for anyone who is studying or has interest in the application of thin film PV.

Each chapter provides a coherent and authoritative account of the topics covered. Together they provide a stimulating view of new possibilities in thin film PV to meet the challenges of increasing the adoption of PV solar energy and reducing our carbon emissions from the use of fossil fuels. These challenges include the need for both high beginning-of-life efficiency and stable long-term performance. This directly impacts the levelised cost of electricity and the carbon impact. In the long term, with the expected growth in thin film PV production, we must look to improving sustainability through the choice of abundant materials and minimising the use of materials through greater efficiency of utilisation both within the device and in manufacturing.

The idea for this book came from the excellent research collaboration in the UK on thin film PV under the Research Councils UK Energy Programme, PV SUPERGEN. This project ran for a total of eight years from 2004 to 2012 and brought together many inspiring ideas that could potentially transform thin film PV production. As with all research projects there is always so much more that could be done and new materials to explore, but the legacy of this research are the research teams that have built on these early successes. Many of the chapters of this book are authored by members of the PV SUPERGEN collaboration and I extend my gratitude to all of the 50 plus researchers who have contributed to this research. The thin film PV research community is the richer and stronger from this formative collaboration and I hope this book will be an inspiration to all those who are interested in the topic.

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CHAPTER 1

Introduction and Techno-economic Background

STUART J. C. IRVINE*[a] AND CHIARA CANDELISE[b]

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1.1 Potential for PV Energy Generation as Part of a Renewable Energy Mix

Climate change became one of the major drivers for changing the balance of energy generation and supply in the latter part of the 20th century and the beginning of the 21st century. The increase in carbon dioxide (CO_2) concentration in the atmosphere over the past century to a figure approaching 400 parts per million (ppm) is taking it closer to the historical 450 ppm concentration where there was virtually no ice on the planet. The Intergovernmental Panel on Climate Change (IPCC) has set a maximum increase in global temperature of 2 °C which Hansen *et al.*[1] argue can only be achieved if atmospheric CO_2 falls to 350 ppm to avoid irreversible loss of the ice sheet. Meinshausen *et al.*[2] put a figure on cumulative CO_2 emissions into the atmosphere of 1000 Gt between 2000 and 2050 would yield a 25% probability of exceeding the 2 °C threshold in global warming.

The world electricity supply is heavily dependent on coal, gas and oil, accounting for 62% of the total for Organisation for Economic Co-operation and Development (OECD) countries in the period January to April 2012,

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according to the International Energy Agency (IEA).[3] In the same period the balance was made up of 19% nuclear, 14% hydro and a mere 5% for other renewable energy such as wind, solar and geothermal. However, this small contribution from renewable energy has been increasing and was up by 1% on the same period the previous year. Vries *et al.*[4] have analysed the potential mix of wind, solar and biomass (WSB) to 2050 and concluded that this could be achieved at an energy cost of 10 US cents per kWh of energy, displacing fossil fuel electricity generation.

Although the annual growth of the photovoltaic (PV) sector has been in the range of 30 to 40% over the past 20 years, it is still at an early stage of potential development both in terms of capacity and price. A number of different scenarios exist to predict the future renewable energy mix that will displace combustion of fossil fuels.[5] For example, the World Business Council for Sustainable Development (WBCSD) predicts 50% electricity generated from renewable energy sources by 2050 with 15% generated by solar PV.[6] Other scenarios give a range for renewable energy generation from 31% from the IEA to a number of studies predicting 50%, including the German Advisory Council on Climate Change, Greenpeace and Shell's sustainable development plan. All the scenarios consider PV solar energy to be a significant part of the energy mix though the extent of penetration into the energy mix changes according to the different scenarios. Looking beyond 2050 the proportion of renewable energy and in particular PV solar energy will continue to grow and the German Solar Industry Association predicts that the proportion of PV solar electricity generation will increase to over 50% of the mix by the end of the century. In a separate study by Fthenakis *et al.*[7] which looked at the potential for combined PV and concentrator solar power (CSP) in the USA, it was predicted that all the electrical energy could be produced from the Sun combined with compressed air energy storage.

In 2011 over 25 GW of PV was installed worldwide, taking the cumulated PV installations to over 50 GW. Most of these installations are based on crystalline silicon (c-Si), but the share of thin film PV has grown over the past decade and currently stands at between 10 and 15%.

In terms of climate change there is a carbon cost in manufacture based on the dependence of electricity used in PV module manufacture on fossil fuel sources. The melting of silicon to form the c-Si requires a temperature of over 1400 °C. In contrast, thin film PV uses processing temperatures below 600 °C and therefore will require less energy. Pehnt[8] carried out a lifecycle analysis of c-Si PV module manufacture. With the current German energy mix, where there is 566 g of CO_2 per kWh of electricity, this leads to an emission of 100 g of CO_2 equivalent per kWh of electricity generated over the lifetime of the PV module. As the proportion of non-fossil fuel energy sources in the energy mix increases this could be halved to 50 g of CO_2 equivalent per kWh. This compares with around 10 g of CO_2 equivalent per kWh for onshore wind and 1.5 MW hydropower. Other factors that will reduce this carbon emission are the efficiency of solar energy conversion and processing temperatures. Thin film PV is currently less efficient than c-Si, roughly 10% compared with 15%

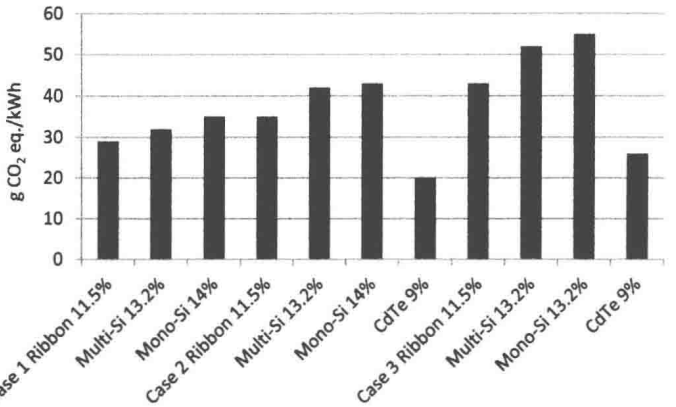

Figure 1.1 Lifecycle emissions (g CO_2 equivalent per kWh) from different types of silicon modules compared with thin film CdTe for: Case 1 – the current geographically specific production of Si; Case 2 – emissions for upstream electricity used in production in Europe; and Case 3 – emissions for equivalent production in the USA (after Fthenakis *et al.*[7]).

but the process energy per square metre is less, which leads to an overall reduction in CO_2 emission. Fthenakis *et al.*[7] estimated that less than 20 g CO_2 equivalent per kWh was emitted for 9% efficient cadmium telluride modules.

Figure 1.1 illustrates that cadmium telluride (CdTe) thin film PV is very competitive in terms of environmental emissions compared with other technologies. Recent improvements in efficiency in thin film CdTe modules to more than 12% would reduce carbon emissions to less than 15 g CO_2 equivalent per kWh. From these estimates it is clear that the adoption of thin film PV modules will make an impact on reducing carbon emissions in PV module manufacture.

In this book we examine the materials challenges for inorganic thin film PV that will influence both the environmental impact and the economic payback, as discussed later in this chapter.

1.2 Historical Development of Thin Film PV

Observation of the photovoltaic effect goes back to Becquerel, first published in 1839.[9] However, practical devices were only realised with the development of high purity silicon for semiconductor devices and the first demonstration of a silicon PV cell at Bell Labs in 1954.[10] The initial devices had a conversion efficiency of 6%, but this rapidly improved and established silicon solar cells as a source of power for the early satellites. By 1980 c-Si cells had reached 16% AM1.5 (air mass) efficiency and have continued to improve to the present day with record efficiency of 25%.[11]

Although the global PV market is dominated by c-Si, there has been rapid growth of other PV cell and module technologies that offer a very wide choice of PV materials, each with its potential advantages and disadvantages

compared with the silicon benchmark. For c-Si, the development of cast multi-crystalline silicon has provided a cheaper alternative to single crystal silicon with only a small penalty in loss of efficiency. By 2004 multi-crystalline silicon single cell record efficiency had exceeded 20%.[12]

The earliest thin film PV dates back to the late 1960s with the emergence of amorphous silicon (a-Si) on glass substrates as a much cheaper and lower energy option than the crystalline silicon cells.[13,14] The first a-Si solar cell reports date back to 1976[15] but have never achieved the efficiency of the c-Si counterparts. This is discussed in more detail regarding the fundamental properties in Chapter 2 and in further detail in Chapter 3. In many respects, the history of a-Si has established a cheaper alternative to c-Si and led the way for the emergence of other thin film materials. The techno-economic trade-off between cost of manufacture and module efficiency is discussed later in this chapter and provides a context for the remainder of the book. Single junction a-Si cells have now achieved over 10% stabilised efficiency[16] and over 12% when combined in a tandem cell with a micro-crystalline junction.[17] Early applications of a-Si solar cells were seen in consumer products where the low cost and monolithic integration were important but longer term stability was not as important as for larger scale power applications. Monolithic integration of a-Si onto glass has enabled a range of architectural applications to be explored that would have been difficult or impossible to achieve with c-Si.

The origins of CdTe PV cells goes back to a Cu_2Te/CdTe cell reported in 1976 by Cusano.[18] This sparked a rapid increase in the possibilities for compound semiconductor thin film PV that included, around the same time, the first interest in the Chalcopyrite structure of copper indium diselenide (CIS) with the work of Wagner *et al.*[19] on single crystal material and Kazmerski *et al.*[20] on thin film PV. Further developments on CIS thin film PV led to alloying with gallium to form CIGS where indium can be substituted with gallium to change the bandgap of the absorber. For both CIGS and CdTe cells the absorber is p-type and the preferred n-type heterojunction material has become cadmium sulphide. Although early commercialisation of thin film PV was with a-Si, the more complex polycrystalline chalcogenides have shown the potential to achieve higher module efficiencies and good long-term stability. Large-scale thin film module manufacture of CdTe and CIGS modules has been demonstrated by First Solar and Solar Frontier, respectively. The significance of manufacturing volume in the cost of module manufacture is discussed in Section 1.4 along with the significance of continual improvements of module conversion efficiency.

The past 20 years have seen the development of many alternative materials and designs for PV solar cells suitable for a range of different applications. The drive for low cost materials and low temperature processing has generated a huge amount of research in dye sensitised solar cells (DSC) and organic photovoltaics. The DSC owes its origins to photoelectrochemical cells and the origins of this go back to Becquerel.[9] The principal of these

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