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Manufacturing metrology for c-Si photovoltaic module reliability and durability, Part I: Feedstock, crystallization and wafering

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ABSTRACT

This article is the first in a three-part series of manufacturing metrology for c-Si photovoltaic (PV) module reliability and durability. Here in Part 1 we focus on the three primary process steps for making silicon substrates for PV cells: (1) feedstock production; (2) ingot and brick production; and (3) wafer production. Each of these steps can affect the final reliability/durability of PV modules in the field with manufacturing metrology potentially playing a significant role. This article provides a comprehensive overview of historical and current processes in each of these three steps, followed by a discussion of associated reliability challenges and metrology strategies that can be employed for increased reliability and durability in resultant modules. Gaps in the current state of understanding in connective metrology data during processing to reliability/durability in the field are then identified along with suggested improvements that should be considered by the PV community.

Contents

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1. Introduction

Silicon, the most earth-abundant element in the periodic table after oxygen, accounts for 25.7% of the earth's crust and is mainly found as silicon oxides, in the form of silicate minerals. The production and purification of silicon dates back to the 1800s; however, current commercial methods were primarily developed in the 1900s. The process for making silicon substrates for PV cells can be divided into three different steps: (1) feedstock production, (2) ingot production, and (3) wafer production. Each of these steps can in some way affect the final reliability/durability of PV modules in the field. Here we review each of these steps successively.

The scope for silicon feedstock production typically encompasses all processes needed to transform sand into polycrystalline chunks of silicon. These are in essence refining processes that are mainly classified in terms of grade or purity, process phase (metallurgical route, gaseous route, etc.), cost, and energy consumption. This article reviews the majority of feedstock production processes used to create metallurgical grade silicon (MG-Si), upgraded metallurgical grade silicon (UMG-Si), and electronic grade silicon (EG-Si) before focusing on the main competing commercial technologies i.e. Siemens, fluidized bed reactor, and UMG silicon [1]. The Siemens and the fluidized bed processes account for the great majority of polysilicon used in crystalline silicon (c-Si) solar cell production.

The scope for ingot production includes techniques for monocrystalline silicon (mono-Si) such as the Czochralski (CZ) or float-zone (FZ) method, for multicrystalline silicon (multi-Si) such as casting and directional solidification DS, and for quasi-monocrystalline silicon (i.e. mono-like). Ingot production is mainly classified in terms of the resulting crystallinity of the ingot, which can be explained in terms of the grain size. Polycrystalline silicon, typically not used in PV applications, consists of a grain size on the order of nanometers (nm) to microns (μm). Multi-Si consists of grain sizes on the order of μm to millimeters (mm), while mono-Si occurs when the whole ingot is a single grain. Mono-like Si falls somewhere in between multi-Si and mono-Si. Typically, a Mono-like silicon ingot would consist of very large single grain occupying 60–80% of the total volume surrounded by multi-Si. These are not to be confused with nanocrystalline silicon (nc-Si) and microcrystalline silicon (μc-Si), which are forms of porous silicon that cannot be generated during ingot production. In fact, these have a paracrystalline structure, which consists of a mixture of small grains of crystalline silicon and an amorphous phase. Mono-Si CZ accounts for 40% of all c-Si solar cells while 60% are made from multi-Si according to the 2014 edition of the International Technology Roadmap for Photovoltaics (ITRPV www.itrpv.net). Reviews of silicon crystal growth for photovoltaics are available in the literature [2–4].

The scope for wafer production includes techniques for wire sawing such as slurry-based wire sawing and diamond-based wire sawing as well as kerfless wafering techniques such as the implant-cleave method, the exfoliation method, ribbon growth processes, and epitaxial growth processes. Today, most, if not all wafers used for crystalline silicon solar cells are produced using a wire sawing method. Reviews of wire sawing are available in the literature [5,6]. According to the 2014 edition of the ITRPV,