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Intense pulsed light processing for photovoltaic manufacturing

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ABSTRACT

The solar manufacturing industry continues to expand and become a key source of energy as manufacturing costs have decreased. This has led to a rapid growth in revenue and a corresponding drop in margins that has suppliers implementing solutions to further reduce the costs associated with manufacturing solar panels. Despite these improvements, solar energy derived from photovoltaics still has an energy pay-back time of at least one year with some of this is associated with heating processes. To further reduce costs, a new technology called intense pulsed light is being implemented to eliminate expensive high energy thermal processes and encourage higher throughput. The technology also includes opportunities for devices that contain thermally limited materials. The technique was originally explored when the photovoltaic industry was quite small, and has only recently begun to gather interest as the printed electronics industry realized gains. This review discusses the use of intense pulsed light in photovoltaic manufacturing, detailing the process from a photonic physics perspective, the relevant heat transfer mechanisms, as well as its impact on the major photovoltaic sectors. Demonstrations of generation 1: crystalline silicon solar cells, generation 2: thin film solar cells, and emerging technologies: hybrid organic solar cell applications are discussed. Lastly, future outlooks for intense pulsed light in the photovoltaic manufacturing sector are offered.

1. Introduction

The photovoltaic manufacturing industry has produced significant cost savings in the past decade, which has coincided with the growth of the installation base. These savings have been primarily driven by the rapid expansion of manufacturing in the crystalline silicon space and supplemented by incremental technical innovations [1,2]. The impact has had a positive effect on revenues while falling margins shift the emphasis to further reductions in manufacturing costs. Meanwhile, the energy pay-back time (EPBT) for manufacturing the silicon modules is currently between 2 and 4 years, and continues to fall [3,4]. However, very high energy thermal processes throughout the manufacturing process, from the growth of the ingot through cell processing and the panel assembly, is still prevalent in the industry [5,6]. Newer thin film technologies have reduced the EPBT further but still rely on thermal processes related to materials deposition [4,7]. Thus across the first two generations of photovoltaics, the thermal processes are prominent in terms of the EPBT. Many emergent solar cell technologies use lower cost materials that can be deposited using roll-to-roll techniques with low thermal budgets; significantly reducing the EPBT [8–10]. Proposed techniques for these newer technologies inevitably rely on annealing processes albeit these may involve lower thermal budgets. Additionally, many of the emerging materials for these devices have temperature limitations of a few hundred degrees Celsius. Alternative techniques that reduce the energy requirements from thermal processing remain important for the industry to further decrease EPBT and are a forward path for newer photovoltaic technologies.

A localized heating technique, Intense Pulsed Light (IPL), also known as flash light sintering and photonic sintering, has been very successful in the printed electronics industry [11]. In this application, metal nanoparticle films are deposited onto flexible substrates using well known printing techniques such as screen printing, gravure and inkjet printing [12–16]. These films are then subjected to the IPL process in which the materials often undergo both chemical and solid state modifications, resulting in conductive bulk thin films. The developed inks and range of depositions with the scalability of the IPL process yield prospects of large scale production in roll-to-roll manufacturing on flexible substrates. Opportunities for this technology exists in several areas such as antennas for radio frequency identification, interconnects for flexible electronics, and 3-D applications [17,18].

The IPL technique delivers high-energy light in a very short duration over a large processing area, heating thin films containing

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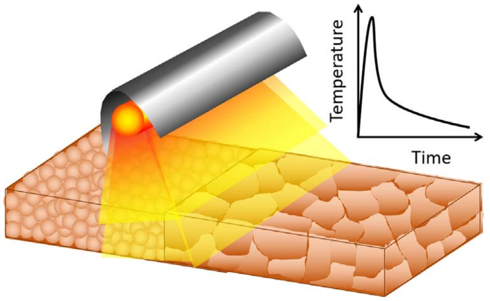

Fig. 1. Schematic of the intense pulsed light process over a large area of deposited nanoparticles inducing rapid localized temperature rises resulting in changes to film morphology.

photosensitive nanoparticles with measured temperatures of several hundred degrees centigrade [19,20]. Sufficient heat is produced within the thin film promoting densification and grain growth of the nanoparticles (Fig. 1). The light energy absorbed by the thin films results in a near instantaneous rise in temperature that lasts for the duration of the pulse, commonly on the order of a few milliseconds. These thin films exist on a substrate carrier having a thermal mass several orders of magnitude larger, hence the time to establish thermal equilibrium between the film and the substrate exceeds that of the flash. Consequently, the high temperatures are not transmitted into the substrates as the amount of heat energy introduced is quickly dissipated [21]. Thus the process focuses heat only where it is necessary, which is the thin film and can be implemented on more fragile organic substrates such as polymers and papers.

Most of the functional materials used in photovoltaics absorb light energy; and for this reason the IPL process has ample opportunities to displace traditional thermal processes to positively affect the EPBT. The performance of photovoltaics is highly influenced by the purity and precise composition of the electronic materials, grain size and well-defined interfaces. The IPL technique must also be able to produce defect free films, which is not as important for single compound metal conductive films. The second generation and emerging solar cell technologies typically use photoactive semiconductors which include more than one compound; adding complexity to any thermal process and often requires modified environments to prevent sublimation. Thus not only must the IPL process increase the grain size of deposited nanoparticle inks, it must produce compositionally exact materials. However, these more complex materials include advantages related to materials usage, defect tolerance and flexibility [22]. Recent progress in the IPL technique with nanoparticle inks warrants a closer look of the process as it has progressed in over the past 40 years with technology advancements yielding more control to the process engineer and newer materials available to photovoltaic designers. With this in mind, several groups have endeavored to study IPL for the industry because the speed of the process offers advantages that can positively affect the performance, manufacturability and EPBT.

In this review, the IPL process is described within the context as a tool for the solar cell manufacturing industry. The parameters of the process related to the photovoltaic materials and xenon source are described and the general model of the thermal response is described. Details regarding the change in temperature of the films as determined by direct measurement and modeling is presented along with the observed changes to the materials. A brief discussion of IPL specifics within the printed electronics industry is presented both from a description of the process and as a potential to the photovoltaic industry. The process is reviewed with materials used in the first generation crystalline silicon (c-Si), second generation thin film and emerging technologies organic (OPV), dye sensitized (DSSC) and perovskite solar cells. This includes the examination of the electronically functional components within the architecture of solar cells such as absorbers, conductors, hole blocking and support layers. The results collected in this review are summarized and an outlook of future opportunities is given.

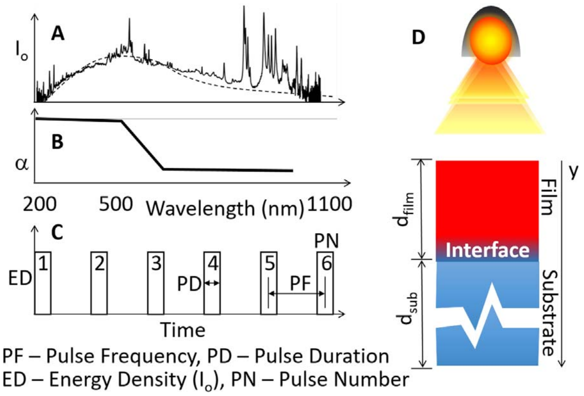

Fig. 2. Schematic of the parameters involved in the IPL process. (A) shows the general wavelength behavior of the Xenon source; (B) is the absorptivity of the film; (C) the parameters from the light source, film and substrate built into the model; (D) view of the IPL process orthogonal to the film in the direction of the light energy.

2. Intense pulsed light process

The use of IPL in the thermal processing of semiconductor device surfaces has been around since the 1970's [23]. Although some reports of the IPL process were explored initially, manufacturers turned to rapid thermal annealing as an economically scalable technique to anneal semiconductors [24]. IPL is a non-contact form of rapid heating in which fast millisecond pulses of broad spectrum light, 190–1100 nm, are produced from a Xenon plasma bulb and absorbed by the material. The incident radiation $I_o(\lambda)$ is directly related to the spectrum of light $(S(\lambda))$ a fixed property of the lamp (with a general shape shown in Fig. 2A) where the energy density (ED) of the light is a function of the voltage applied to arc the Xenon source. The conversion of the electrical to optical radiation is at least 30%; extending from the ultraviolet through the visible into the near infrared over a large area without the use of sophisticated optics [25]. The intensity of the flash can be adjusted to regulate the ED over a nominal range of 1–30 J/cm^2 from single lamps, and systems of multiple lamps capable of upwards of 150 J/cm^2. The duration of each pulse (PD) is on the order of hundreds of microseconds to tens of milliseconds. The number of pulses (PN) and the pulse frequency (PF) can be varied for finer control over the induced film temperatures to selectively move a process through stages such as evaporation of solvents, removal of organics, chemical reactions, sintering and/or melting. A representative square wave pattern of the applied pulses is shown schematically in Fig. 2C.

The speed and processing areas make IPL appropriate for incorporation into roll-to-roll capable printing processes. Traditional roll-to-roll deposition processes that have been successfully scaled in several industries rely on solution phase techniques in which a solid is incorporated into a carrier solvent. Nanoparticles are versatile for incorporation into solution phase deposition processes and are also advantageous to the IPL process since less energy is required to sinter the smaller particles due to their relatively larger surface to volume ratio. Light with energies greater than or equal to the bandgap (E_g) are absorbed within the thin film, causing multiple electrons to be promoted from the valence to conduction band. Electrons with energies larger than the conduction band edge, release their excess energy in an attempt to fill the many available band states near the conduction band edge. The excess energy is released as phonons leading to localized heating of the material [26]. This process occurs in time scales of less than 10^{-10} s, therefore, it is considered to be an instantaneous event in relation to the processing time scales. The light energy absorbed is governed by the absorptivity and thickness of the films, where the