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## Characterizing amorphous silicon, silicon nitride, and diffused layers in crystalline silicon solar cells using micro-photoluminescence spectroscopy



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#### ABSTRACT

We report and explain the photoluminescence (PL) spectra from crystalline silicon (c-Si) wafers passivated by hydrogenated amorphous silicon (a-Si:H) films under various measurement conditions, utilizing the different absorption coefficients and radiative recombination mechanisms in c-Si and a-Si:H. By comparison with the luminescence properties of a-Si:H, we also demonstrate that SiN<sub>x</sub> films deposited under certain silicon-rich conditions yield luminescence spectra similar to those of a-Si:H, indicating the presence of an a-Si:H-like phase in the SiN<sub>x</sub> films. This causes a reduction in the blue response of the solar cells via parasitic absorption. In addition, with the ability to detect the specific emission from heavily-doped silicon via band-gap narrowing effects, we can unambiguously separate individual spectral PL signatures of three different layers in a single substrate: the SiN<sub>x</sub> passivation films, the diffused layers, and the underlying c-Si substrate. Finally, we apply this technique to evaluate parasitic absorption in the passivation films, and the doping density of the diffused layers on different finished solar cells, highlighting the value of this nondestructive contactless, micron-scale technique for photovoltaic applications.

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### 1. Introduction

There has been a growing interest in employing micro-phot'oluminescence spectroscopy ( $\mu$ PLS) as a precise and nondestructive characterization tool in silicon photovoltaics (PV). Utilizing the high spatial and spectral resolutions of the  $\mu$ PLS technique, the microscopic properties of micron-scale features on crystalline silicon (c-Si) wafers and cell pre-cursors have been investigated, such as dislocations [1–4], iron precipitates [5], internal stress [6], laser-doped regions [7–11], or locally diffused layers [12]. Besides that, luminescence of hydrogenated amorphous silicon (a-Si:H) films has also been intensively studied for many decades, and is well known as an effective tool to study fundamental properties of this material.

Over the past decades, a-Si:H/c-Si heterojunctions have come to play an important role in silicon PV, since they not only feature high quality and stable electronic properties, but also utilize low temperature deposition processes (typically < 200 °C). These

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http://dx.doi.org/10.1016/j.solmat.2015.11.006 0927-0248/© 2015 Elsevier B.V. All rights reserved. junctions are the key building blocks of record efficiency silicon heterojunction solar cells [13–15]. Furthermore, a-Si:H has been demonstrated as an excellent passivation layer in silicon homojunction solar cells, which can achieve very good majority carrier conduction [16]. On the other hand, diffused junctions and  $SiN_x$ passivation layers are two very important components in today's standard industrial silicon solar cells. Therefore, an insightful understanding of the combined PL spectra from c-Si wafers containing these layers (diffused layers, a-Si:H, and  $SiN_x$  films) may prove useful in the development of precise characterization tools for PV applications.

Although the electronic and optical qualities of these layers can be evaluated directly after they are formed, using commonlyknown techniques such as electrochemical capacitance–voltage (for diffused layers) [17] or spectroscopic ellipsometry and infrared spectroscopy (for a-Si:H and SiN<sub>x</sub>) [18–22], their properties can be affected by successive fabrication steps. However, it is difficult to nondestructively assess the properties of these layers in finished solar cells since they are often buried underneath other materials or layers. Furthermore, as the complexity of device structures increases, it is more difficult to probe micron-scale features on finished solar cells and cell pre-cursors such as locally-doped regions.

In this study, we first report and explain the combined PL spectra emitted from a-Si:H films and the underlying c-Si substrate, including the effects of different measurement and sample preparation conditions. We then demonstrate that SiN<sub>x</sub> films deposited under silicon-rich conditions yield PL spectra similar to those of a-Si:H films, suggesting the presence of an a-Si:H-like phase, and indicating that the  $SiN_x$  films can reduce the blue response of the solar cells via parasitic absorption. In addition, combining this method with our recently established technique for detecting heavily-doped layers in silicon wafers [12], we can unambiguously separate individual spectral PL signatures of three different layers in a single substrate: the  $SiN_x$  passivation films, the diffused layers, and the underlying c-Si substrate, all with micron-scale spatial resolution. Finally, we apply this technique to evaluate unwanted absorption in the passivation films and the doping density of the diffused layers on different solar cell designs, in which some investigated features are only a few tens of microns wide. These applications highlight the value of this contactless and nondestructive technique, which can be applied directly both on finished cells and cell pre-cursors, to study and optimize the fabrication process. A critical aspect of this technique is the use of low temperatures (78 K and above), since the individual spectral PL signatures from different layers are not discernible at room temperature, due to both thermal broadening of band-to-band luminescence, and thermal quenching of defect luminescence [11,12].

#### 2. Experimental details

The experimental set up of our  $\mu$ PLS system is described in detail elsewhere [4,12]. The spectral resolution of this system is 0.25 nm. Two different excitation lasers were employed in this work, a 532 nm continuous-wave diode-pump solid-state (CW-DPSS) laser and an 830-nm CW laser diode. For both lasers, the beam diameter on the sample surface is about 1  $\mu$ m, and the excitation power is about 6 mW. The spectral response of the entire system was determined with a calibrated halogen-tungsten light source. The sample temperature was controlled by a liquid-nitrogen cryostat.

The investigated wafers are p-type boron-doped c-Si wafers with resistivities  $\geq$  100  $\Omega$  cm. They were chemically etched in an HF/HNO<sub>3</sub> solution to remove saw damage and to achieve planar surfaces. Their final thickness is about 300 µm. Some were passivated by thin a-Si:H films, whose thicknesses vary from 10 to 100 nm, by plasma-enhanced chemical-vapor deposition (PECVD). Some were passivated by thin PECVD SiN<sub>x</sub> films with various SiH<sub>4</sub>:NH<sub>3</sub> gas flow ratios in order to achieve different optical properties. Some were heavily doped with phosphorus from a POCl<sub>3</sub> vapor source to form n + layers on the surfaces, and then immersed in diluted HF to remove the phosphosilicate glass layers. The resultant sheet resistance is about 45  $\Omega$  / $\Box$ . These n+ diffused wafers were then passivated by PECVD SiN<sub>x</sub> films with various SiH<sub>4</sub>:NH<sub>3</sub> gas flow ratios. The thicknesses of these thin SiN<sub>x</sub> films were determined by an ellipsometer. The investigated c-Si solar cell structures are the passivated-emitter rear locallydiffused (PERL) cell [23], interdigitated back contact cell with a diffused front surface field (FSF-IBC) [24,25], and interdigitated back contact cell without a front surface field (IBC) [26]. All devices have efficiencies above 20%.

The investigated a-Si:H and SiN<sub>x</sub> films were prepared at three different laboratories including The Australian National University (ANU), Australian National Fabrication Facility (ANFF), and École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. Table 1

#### Table 1

Substrate temperatures and frequency modes of PECVD reactors employed in this study.

Film	Substrate temperature (°C)	Frequency mode
ANU a-Si:H	300	Microwave/radio frequency dual- mode
ANFF a-Si:H	400	Capacitive-coupled plasma
EPFL a-Si:H	200	Capacitive-coupled plasma
ANU SiN <sub>x</sub>	300	Microwave/radio frequency dual- mode
ANFF $SiN_x$	400	Capacitive-coupled plasma



**Fig. 1.** Comparison of normalized PL spectra (a) from a-Si:H deposited at different laboratories and (b) between intrinsic a-Si:H and doped/intrinsic a-Si:H stacks. The a-Si:H films were deposited directly on glass substrates. The excitation wavelength is 532 nm and the measurement temperature is 79 K. The spurious peak at 1064 nm is due to the not-entirely-suppressed 1064-nm component from the 532-nm DPSS laser.

gives a summary of substrate temperatures and frequency modes of the PECVD reactors employed in this study.

#### 3. Luminescence of a-Si:H deposited on glass substrates

For many decades, luminescence spectra from a-Si:H have been studied intensively regarding their spectral shapes, peak locations, and relative intensities under different measurement conditions and with various preparation conditions and techniques. Therefore, in this first section, we aim to review only the basic PL spectra captured from a-Si:H deposited directly on glass substrates, which will serve as a basis for our later discussions on the combined PL signal from different layers stacked together.

Fig. 1a shows the normalized PL spectra from intrinsic a-Si:H films deposited on glass substrates, excited by the 532-nm laser at 79 K, prepared at ANU ( $\sim$ 70 nm), ANFF ( $\sim$ 30 nm), and EPFL ( $\sim$ 10 nm). The first notable feature is that, at 79 K the spectra of a-Si:H are much broader than those of c-Si. The full width at half maximum (FWHM) of the a-Si:H peak is  $\sim$ 300 meV, whereas that

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