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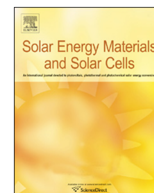

Photoluminescence imaging of thin film silicon on glass

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ABSTRACT

Photoluminescence (PL) imaging over a large area (4.5×4.5 cm^2) is demonstrated on polycrystalline silicon thin films and solar cells on glass. PL imaging is a well-established technique for characterisation of silicon wafers and wafer-based solar cells, however its application to crystalline silicon thin films on glass was not possible due to low material quality and volume, and IR noise from the glass substrate. This paper reports methods to overcome these limitations, the design of a thin-film silicon PL imaging system, examples of PL images of silicon films at different processing stages and preliminary findings. It is demonstrated that the observed PL images qualitatively correlate with the silicon film crystal grain structure and quality.

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1. Introduction

Photoluminescence (PL) imaging of polycrystalline silicon (poly-Si) films on glass represents a breakthrough in our ability to characterise the material important to poly-Si thin-film devices such as solar cells and thin-film transistors. The technique has the advantage of being non-contact and non-destructive, allowing characterisation of samples before and after each step in the device fabrication sequence. PL imaging is already an important part of silicon wafer-based solar cell characterisation, and provides a spatially resolved map of properties such as minority carrier lifetime (τ_{eff}) [1], implied Open Circuit Voltage (V_{oc}), effective series resistance (R_s), emitter sheet resistance [2], and shunt detection [3]. Until recently it was not possible to apply PL imaging to poly-Si films and solar cells because the material quality was poor, which when combined with the small film thickness and volume leads to a very low PL intensity. This issue is compounded by a large amount of fluorescence from glass. This has been the case for poly-Si films obtained by solid-phase crystallisation (SPC). Recently, much better quality poly-Si films have been developed by liquid phase crystallisation [4–7] for which the spectrally resolved PL signal was observed, showing a significantly higher band-band intensity [8]. Solar cells fabricated from liquid-phase crystallised Si on glass (LPCSG) have outperformed cells made of SPC Si [9]. The PL imaging equipment for Si wafers is incompatible with Si films because the excitation light not completely absorbed within the film induces fluorescence in the glass substrate. This paper describes the specific design features of the PL imaging tool for poly-Si films and demonstrates a correlation among the PL images, the material structure and the quality. A comparison of PL intensity resulting from 3 different excitation wavelengths (λ_e) is also included, and limitations of the technique to obtain a quantitative measure of material properties are mentioned.

2. Experiment

Samples investigated with the PL imaging system are 10 µm thick, boron doped (1–3E16 cm^{-3}) poly-Si films on 3.3 mm thick Schott Borofloat glass coated with a buffer dielectric layer. Si is deposited via electron beam evaporation at 650 °C and 500 nm/min [6]. It is crystallised by a line-focus diode laser [5–7]. A typical sample is 5×5 cm^2 and contains three laser-scanned well-crystallised Si strips where cells are made. There is about 1 mm wide region of poorly crystallised material between the strips. After crystallisation a solar cell emitter is created by thermal phosphorus diffusion followed by hydrogen passivation of the films. PL imaging is applied to as-crystallised samples as well as the samples after emitter diffusion, and hydrogen passivation. A SiN_x coating (90 nm) is deposited on the Si film via PECVD, forming a temporary surface passivation, during PL characterisation, which is removed by HF before further processing steps.

3. Challenges facing PL imaging of thin film silicon

PL imaging provides a spatially resolved map of the intensity of band–band luminescence, and has historically been difficult/impossible

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to apply to poly-Si films. This is due to low material lifetime, high fluorescence of glass, and unsuitability of Si wafer PL excitation sources for poly-Si films. Previously used SPC poly-Si has a very short τ_{eff} of less than 10 ns due to carrier recombination through shallow bands [10] which do not contribute to the band–band PL intensity. Recent developments in LPCSG have resulted in a material with much longer lifetimes, at least 260 ns [6] and a larger number of carriers recombining radiatively at the band edges, rather than through defect levels [8]. A spectrally resolved band–band PL signal from LPCSG material has previously been reported by Schönau et al. [11]. λ_e longer than 800 nm are commonly used for PL imaging of Si wafers. However, approximately 40% of 800 nm excitation light is not absorbed within 10 μm of c-Si [12]. In LPCSG samples, this unabsorbed light excites fluorescence in the glass substrate which can be an order of magnitude larger than the PL from the poly-Si film. The solution is to use shorter λ_e where the higher absorption in Si results in less transmitted light to cause glass fluorescence. Schönau et al. [11] previously demonstrated the viability of a 500 nm laser as a PL excitation source on poly-Si films, but the excitation area was limited to 0.09 mm^2. By scanning the laser spot over the cell area, a spatially resolved PL intensity map of 2 mm^2 was produced. However this is a fundamentally different technique to that presented here where a whole large area image is taken and a map created during a single exposure. Using a LED array as a excitation source for PL imaging has previously been demonstrated on Si wafers ($\lambda_e = 850$ nm) [13]. A similar approach using a LED array with $\lambda_e \leq 630$ nm is used in the presented imaging system.

4. Design of PL imaging system

The PL imaging tool comprises two main sections, the excitation source and the imaging system. The excitation source consists of components 1–3 , and the imaging system consists of components 5–7 in Fig. 1. Component 1 is a LED array with $\lambda_e = 465$ nm, or 530 nm, or 630 nm. The LED has an optical power of 7–10 W, centred at the wavelengths given above, with a spectral width of about 10 nm. The LED light is directed into a square tube (Kaleidoscope), with specular reflective sides (component 2). This element integrates the incoming light as it passes through, so that the illumination intensity at the tube exit is uniform [14]. The uniformity of the excitation light exiting the kaleidoscope over the sample area varies by less than 5%.

The LED light contains a significant amount of IR noise which is many orders of magnitude larger than the PL signal from the Si film. The final element in the excitation source is a Schott Glass KG5 shortpass filter (component 3) to block most of the IR noise. With an excitation intensity of 1000 W/m^2 at 530 nm, IR noise from the excitation components is approximately 17 counts/s. This signal intensity is the noise floor of the system, and is referred to as background noise. The PL signal from the film is collected and focused by the imaging lens (component 5). A Canon 60 mm f2.8 macro lens is currently used. After the lens is a Schott Glass RG1000 longpass filter (component 6), which blocks any stray light and excitation light not absorbed in the film before the signal is captured by the CCD camera (component 7). Depending on the manufacturer, the quantum efficiency (QE) for a back illuminated CCD can range from 5% to 10%, compared to a front illuminated CCD having a maximum QE of 2% at 1050 nm, so a back illuminated CCD camera is used in this system. Back illuminated CCDs have the Si absorber substrate before the CCD electronics in the optical path which increases the amount of IR collected by the CCD. The camera in the system is a 1 MP back-illuminated CCD Alta F47-HC from Apogee Imaging Systems, with a 13 × 13 μm^2 pixel size. All images and results presented here were taken with the CCD at −20 °C to reduce thermal noise.

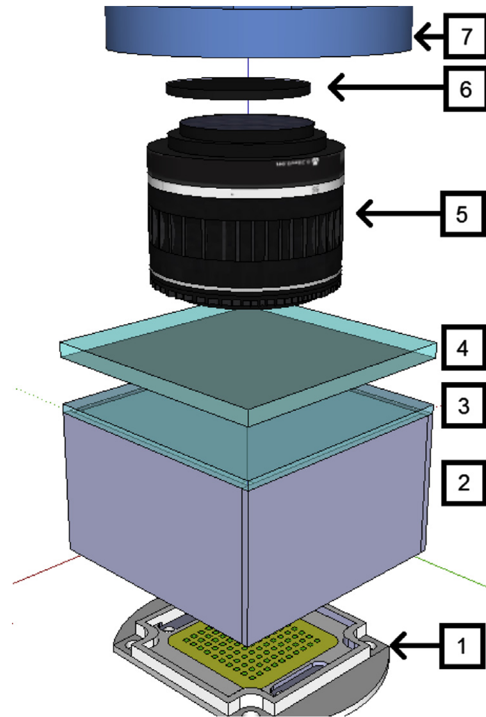

Fig. 1. A schematic view of the poly-Si film PL imaging system: **1**. 100 W LED excitation source, **2**. Mirrored tube (Kaleidoscope), **3**. Shortpass KG5 Schott glass filter, **4**. poly-Si film on glass sample: Si side is down, so the excitation light is incident on the Si, **5**. SLR camera Lens, **6**. Longpass RG1000 Schott glass filter, and **7**. Apogee Camera.

5. Quantifying bulk material quality

The PL intensity (I_{PL}) at any point in the image is linearly proportional to the excess minority carrier concentration (Δn) and the doping density (N_D) given by [15]

$$I_{PL} = A \cdot B \cdot \Delta n \cdot (\Delta n + N_D) \approx \Delta n \cdot N_D \quad (1)$$

The films investigated here are p-type with a boron concentration of 1.65E16 measured by SIMS. The approximation given in Eq. (1) is made assuming $N_D \ll \Delta n$, which is the case here. The coefficient A is a calibration constant determined by the experiment, and the radiative recombination coefficient (B) can be considered as constant for excess carrier concentrations less than 10^{15} cm^{-3} [16]. Thus PL images produced by the described system are a spatially resolved, qualitative measure of the Δn. Quantifying the dependency of Δn on other material properties such as bulk lifetime (τ_{bulk}), minority carrier mobility (μ_n), and glass-side and air-side surface recombination velocities (S_g and S_a respectively) is not possible due to a number of complicating factors unique to poly-Si films on glass. Firstly, S_g is determined by the passivation quality of the intermediate layer between the glass and the Si, and cannot be altered after silicon deposition. Therefore, methods of determining μ_n on wafers using PL, which intentionally increase the surface recombination velocity on the unilluminated side [15], are not applicable to poly-Si films on glass.

Hall measurements on LPCSG samples have revealed non-uniform majority carrier mobility (μ_p) across the film. These Hall measurements of two (0.4 × 0.4 mm^2) points, on the same sample (Fig. 2), show a qualitative correlation with the spatial variation of PL intensity, which is shown in Table 1. The correlation of a higher PL intensity and an increased carrier mobility suggests that the τ_{eff} is not surface limited. If the material were surface limited, the increase in mobility observed at point 1 would result in a lower PL intensity than point 2 due to increased diffusion to, and

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