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Effects of hydrogenation on poly-Si/SiO$_x$ passivating contacts for silicon solar cells

Thien Truong,[1] Di Yan,[1] Andres Cuevas,[1] Daniel Macdonald,[1] and Hieu T. Nguyen[1]

[1]The Australian National University, Canberra, ACT 2601, Australia

E-mail: thien.truong@anu.edu.au

In this work, we characterize and discuss the influence of hydrogenation by means of a hydrogenated silicon nitride (SiN$_x$:H) capping layer followed by a forming gas annealing (FGA) step on doped polycrystalline silicon (poly-Si) films for passivating contacts solar cells. The silicon films are found to contain both amorphous and crystalline phases, each yielding a distinct luminescence peak at low measurement temperatures. We then employ various independent characterization techniques to verify the presence of hydrogen inside the films after the hydrogenation process. The results demonstrate that hydrogen can be introduced into the doped poly-Si films to improve the quality of the poly-Si/SiO$_x$ passivating contacts. We have corroborated the technique on various initial low quality doped poly-Si films, all of which have been improved significantly after the hydrogenation process. These characterization and hydrogenation techniques open an exciting avenue for optimizing passivating-contact structures.

Poly-Si structural and optoelectronic properties

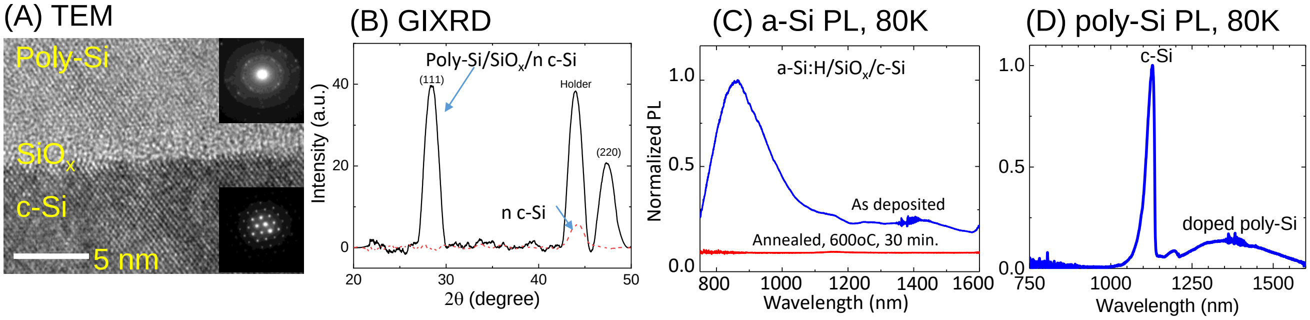

Figure 1. Structural and optoelectronic properties of poly-Si/SiO$_x$ passivating contacts.

First, we demonstrate that the a-Si:H film deposited by the plasma enhanced chemical vapor deposition (PECVD) technique is not fully crystallized after the phosphorus diffusion process. Figure 1A shows a high-resolution transmission electron microscopy (TEM) image of the interface. The interfacial oxide film can be observed as a thin stripe of amorphous structure between the poly-Si and c-Si, as noted in the figure. The doped poly-Si layer shows both crystalline and amorphous phases, whereas as expected, the c-Si substrate shows a very uniform crystalline structure. The attached diffraction patterns confirm the crystallinity of the films. Figure 1B presents the grazing incidence X-ray diffraction (GIXRD) result with clear peaks of Si (111) and Si (220) on the spectrum of the 40-nm phosphorus-doped poly-Si/ 1.3-nm SiO$_x$/ c-Si sample in the 2θ range of 20-50 degrees. These peaks confirm the polycrystalline nature of our poly-Si film. On the bare <100> c-Si substrate, they are not revealed. Figure 1C displays the photoluminescence (PL) spectra from an a-Si:H film deposited by PECVD at 300 °C on top of a SiO$_x$/c-Si sample before and after an annealing step at 600 °C in N$_2$ for 2 h. At this temperature, the amorphous Si film is not largely recrystallized yet, but hydrogen atoms can be expected to escape out of it. The result in Figure 1C shows that this is indeed the case because the a-Si:H PL peak located at ~850 nm is completely quenched by the 600 °C N$_2$ annealing step. Therefore, it is sensible to assume that after the even higher temperature (>800 °C) used for dopant diffusion, there will be essentially no hydrogen left in the bulk of the poly-Si layer. In addition, Figure 1D shows a PL spectrum captured from the 100-nm n+ poly-Si/1.3 nm SiO$_x$/c-Si sample at 80 K, excited with the 405 nm laser. The sharp peak located at ~1125 nm is the band-to-band emission from the c-Si substrate. The spectrum also contains a very broad peak in the range 1300−1400 nm, originates from the radiative defect states inside the doped poly-Si layer. However, there is no PL emission from the amorphous Si phase in the doped poly-Si film.

Effects of hydrogenation of poly-Si/SiO$_x$ passivating contacts

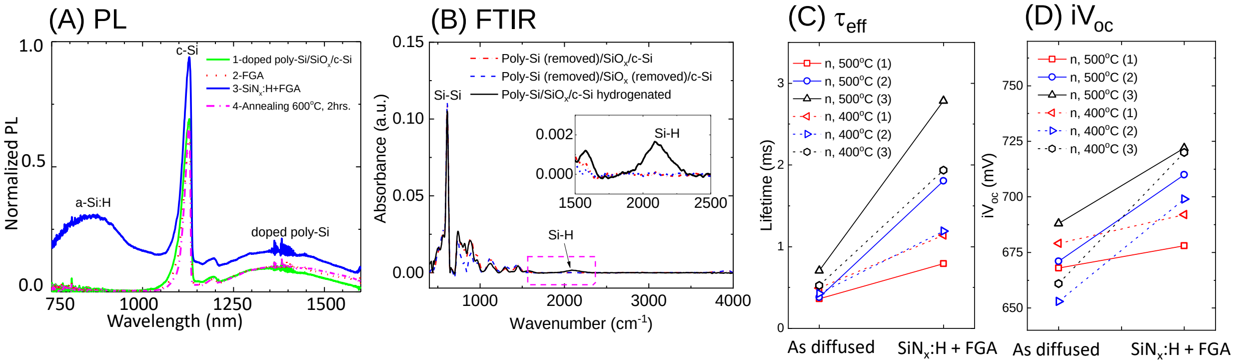

Figure 2. Effects of hydrogenation on performance of poly-Si/SiO$_x$ passivating contacts.

Next, we investigate the effects of hydrogenation on the performance of poly-Si/SiO$_x$ passivating contacts. Figure 2A shows the PL spectra captured from a doped poly-Si sample at various processing steps. The PL spectra of the sample after diffusion and forming gas annealing (FGA) are nearly identical, suggesting that annealing in forming gas at 500 °C does not affect significantly the bulk properties of the doped poly-Si layer and the poly-Si/SiO$_x$ interface, although it is known to improve the SiO$_x$/c-Si interface. However, the spectrum of the sample annealed in the presence of a hydrogen-rich SiN$_x$ film shows a very clear peak located at ~900 nm of a-Si phase, and an increasing in PL intensity from the poly-Si layer. This is strong evidence that the amorphous Si and poly-Si phase has been hydrogenated. To consolidate these conclusions, we bring the sample to anneal in nitrogen at 600 °C for 2 h, the PL spectrum goes back to the initial shape, in which the a-Si:H peak is absent and only the doped poly-Si peak is present. Figure 2B shows Fourier transform infrared spectroscopy (FTIR) results from the hydrogenated phosphorus-doped poly-Si sample at different stages: the poly-Si film is still present, only the film is removed by TMAH etching, and both the film and oxide layer are removed. The captured spectrum presents a clear stretching mode of Si-H bonds (1900 to 2200 cm^{-1}) in the sample with the hydrogenated poly-Si layer. When the layer is removed, the peak also disappears regardless of the presence of the oxide interface. This demonstrates that the amount of hydrogen in the poly-Si layer is still relatively high whereas that in oxide interface is little or below the detection limit of our FTIR tool. Finally, Figure 2C and 2D show a significant improvement in effective minority carrier lifetime (τ_{eff}) at a minority carrier density of 1×10^{15} cm^{-3}, and implied open-circuit voltage (iV$_{oc}$) at 1-sun equivalent intensity from various planar phosphorus-doped poly-Si samples. All samples, initially with either low or high passivation qualities (some with < 0.5 ms and < 670 mV for n-type 1-Ω.cm c-Si substrates), have τ_{eff} and iV$_{oc}$ boosted after the hydrogenation step.

The final presentation will provide an in-depth investigation about the structural and optoelectronic properties of poly-Si on oxide structures, and effects of hydrogenation on performance of poly-Si/SiO$_x$ passivating contacts. Effects of oxide thickness will be demonstrated. Also, the influence of temperature on the PL spectra captured from poly-Si films will be described. Further results on performance of different poly-Si films, either doped by phosphorus or boron, on n or p-type substrate, planar or textured surfaces, after hydrogenation treatments will be presented.