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Field-effect Passivation Characteristics of Black Silicon with Extreme Surface Features

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Black silicon (b-Si) is a nano-scaled surface texture which significantly reduces optical losses in solar cells and provides potential for higher efficiency cells on a range of substrates[1]. Various forms of this texture incorporate extreme surface features that behave fundamentally differently when passivated by dielectric layers with a fixed charge. These include needle like structures formed with reactive ion etching (RIE), or extreme scupting of the surface via metal-catalysed chemical etching (MCCE). This work presents the results from an ARENA funded project in which UNSW works closely with industry partners to characterise, optimise and develop the next generation of surface nanotextures. Specifically, it studies the fundamental interaction between charged surface passivation layers and extreme texture features, particularly where those features are small enough that multiple parts of the surface affect the near surface region. These findings provide fundamental understanding into the passivation of these surfaces and create a foundation for designing novel surface passivation layers for extreme-low-reflectance b-Si solar cells, for downstream module integration and for performance studies.

Although it has been shown that b-Si with extreme features can be effectively passivated by atomic layer deposition (ALD)[2], the excellent surface passivation performance cannot be fully explained by surface passivation theories based on 1D models. It has been hypothesized that the interface fixed charge (Q_f) effectively repels the minority carriers from the entire nanotextured region, thus causing 'depletion spikes', but the mechanism has not yet been demonstrated unambiguously. In this work, experimental investigations of b-Si surface passivation are reinforced with the SENTAURUS TCAD simulation tool to study the field-effect passivation characteristics of non-dffused needle-like features with 2D models, using the planar models and random pyramid (RP) textures as references.

As shown in Figure 1, the 2D random pyramid model has a 1.35 µm height and 2 µm width, and the 2D b-Si model has a 0.5 µm height and 0.2 µm width. Both simulated wafers are non-diffused p-type with 10^{15} cm^{-3} doping. To eliminate the effects of chemical passivation, the fundamental recombination velocities of the electrons and holes are taken to be energy independent and equal to 100 cm/s. The surface passivation layer is 20 nm of Al_2O_3 with Q_f from 10^8 to 10^{13} cm^{-2}.

Our simulations validate results from literature and also reveal new findings. Gastrow *et al.* deposited corona charges to vary the surface charge density and found that the surface recombination of b-Si was more sensitive to high corrona charge densities Q_c ($S_{eff} \propto Q_c^{-4}$) assuming an uniform distribution of the corona charges, and thus they proposed a similar scaling would apply for Q_f[3]. However, our initial simulation results, shown in Figure 2 (a), indicate that the b-Si surface is not more sensitive to high Q_f ($S_{eff} \propto Q_f^{-2}$) compared with a planar surface. Moreover, as shown in Figure 2 (b), the effective recombination-active surface area factor (A_{eff}/A_{proj}) is quantified for the first time in this work (it is determined by the S_{eff} ratio of the textured wafer and the planar wafer [Equation 1]). The change of this area factor indicates a non-linear influence of the surface area (or the total amount of surface defects) on S_{eff}. As the Q_f increases, the effective recombination-active surface area factor decreases significantly for b-Si, which is consistent with a previous hypothesis[3]. However, the relation between Q_f and S_{eff} is far more intricate than a simple Q_f^{-4} scaling. This is likely caused by the non-uniform surface band bending in b-Si. Figure 1 shows that the band bending is uniform and follows the surface

morphology for random pyramids, while the b-Si features get depleted for high Q_f values. Figure 2 (b) clearly shows that the A_{eff}/A_{proj}-Q_f characteristics of b-Si match the band-bending-Q_f characteristics.

$$S_{eff\_textured} = S_{eff\_planar}\frac{A_{eff}}{A_{proj}} \quad (1)$$

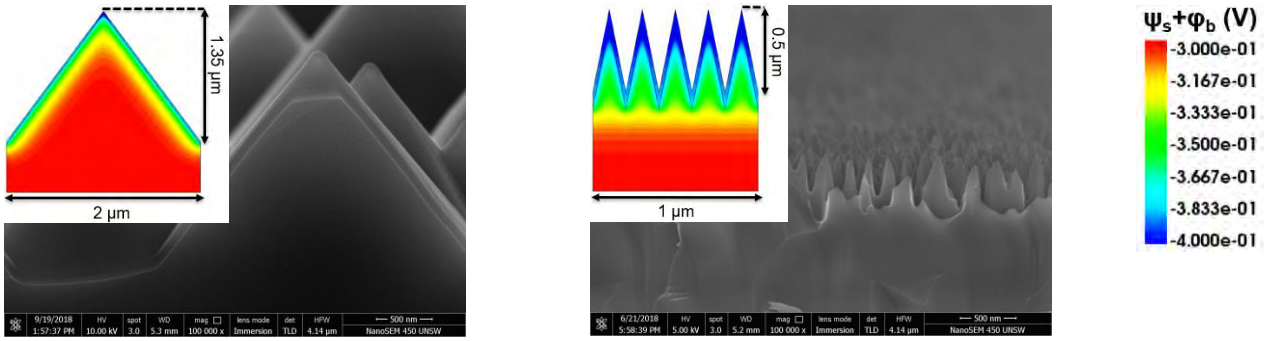

Figure 1. The 2D models of random pyramid and b-Si according to the SEM images of the real surface texturing. The models also show the surface band bending at high Q_f.

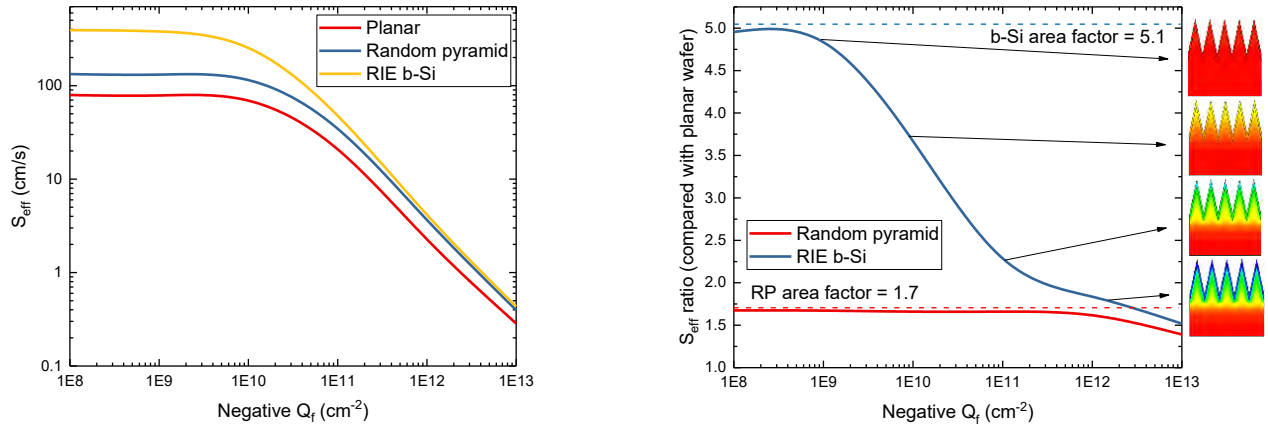

Figure 2. (a) Simulated S_{eff} against Q_f for planar, random pyramid and b-Si, and (b) S_{eff} ratio based on the planar surface for random pyramid and b-Si with different Q_f. The band bending conditions of b-Si are also shown when $Q_f = 10^9$, 10^{10}, 10^{11} and 10^{12} cm^{-2}.

References

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