With the increasing availability of high quality silicon wafers at acceptable cost and excellent surface passivation schemes, the key to bridging the gap between theoretical efficiency (29.4%) and industrial production efficiency (typically 17-20%) of crystalline silicon (c-Si) solar cells is to minimize carrier recombination at the contact regions. The most effective approach is to utilize so-called carrier-selective passivating contacts (CSPCs), which passivate the whole silicon surface and selectively collect one type of photogenerated charge carrier (e.g. the electrons), while blocking the opposite type (e.g. the holes). High-quality CSPCs simultaneously provide excellent surface passivation in both contact and non-contact regions, resulting in reduced carrier recombination and hence high open-circuit voltage ($V_{oc}$) as well as low contact resistivity ($\rho_c$). Consequently, they can be applied to the full surface of the device, enabling a simple fabrication flow with a one-dimensional carrier transportation pattern, resulting in a high fill factor ($FF$).

This work reports recent progress on TiO$_2$-based electron-selective passivating contacts for c-Si solar cells. The performance of thin TiO$_2$ films as electron-selective passivating contact was investigated by considering both the surface passivation quality and the contact resistivity on silicon surfaces. With the optimized TiO$_2$ passivating contacts on n-type silicon wafers, an effective surface recombination velocity ($S_{eff}$) of ~15 cm/s and a contact resistivity of ~26 m$\Omega$·cm$^2$ have been achieved simultaneously. By the implementation of the high-performance TiO$_2$ contacts in the rear, a remarkable efficiency of 22.1% ($V_{oc}$ 674 mV, $J_{sc}$ 39.8 mA/cm$^2$, $FF$ 82.5%) has been achieved on n-type silicon solar cell (see Figure 1). The use of a full-area TiO$_2$ passivating contact eliminates the need for costly thermal-diffusion and contact-opening processing, used in traditional high-efficiency silicon solar cell concept (e.g., passivated emitter and rear cell, PERC), enabling a simple and low-cost fabrication flow.

Furthermore, the industrial feasibility of TiO$_2$ passivating contacts is assessed by investigating their compatibility with firing process, their sensitivity to varying base resistivity and their applicability to ultrathin substrates. The effect of metallization on the performance of TiO$_2$ passivating contacts is also presented. With industry-relevant n-type wafers with a typical base resistivity between 1.0 to 10.0 $\Omega$·cm, an efficiency between 21 and 22% can be easily achieved. An efficiency of 21.5% has also been achieved with an ultrathin silicon substrate (80 $\mu$m). The results demonstrate that dopant-free TiO$_2$ passivating contact is compatible with industrial firing processes, not sensitive to base resistivity, applicable to an ultrathin substrate and very stable. Our findings underscore the great appeal of TiO$_2$ passivating contacts for industrial implementation with their combination of high efficiency with robust fabrication at low cost.

Figure 1 The structure of n-type silicon solar cell featuring a full-area TiO$_2$ contact at the rear (right) and light I-V curves under AM 1.5G (left).