

P-Type Versus n-Type Silicon Wafers: Prospects for High-Efficiency Commercial Silicon Solar Cells

J. E. Cotter, J. H. Guo, P. J. Cousins, M. D. Abbott, F. W. Chen, and K. C. Fisher

Abstract—Chemical and crystallographic defects are a reality of solar-grade silicon wafers and industrial production processes. Long overlooked, phosphorus as a bulk dopant in silicon wafers is an excellent way to mitigate recombination associated with these defects. This paper details the connection between defect recombination and solar cell terminal characteristics for the specific case of unequal electron and hole lifetimes. It then looks at a detailed case study of the impact of diffusion-induced dislocations on the recombination statistics in n-type and p-type silicon wafers and the terminal characteristics of high-efficiency double-sided buried contact silicon solar cells made on both types of wafers. Several additional short case studies examine the recombination associated with other industrially relevant situations—process-induced dislocations, surface passivation, and unwanted contamination. For the defects studied here, n-type silicon wafers are more tolerant to chemical and crystallographic defects, and as such, they have exceptional potential as a wafer for high-efficiency commercial silicon solar cells.

Index Terms—Photovoltaic cells, silicon.

I. INTRODUCTION

N-TYPE Czochralski and multicrystalline silicon as materials for solar cells have received considerable attention recently due to emerging evidence that they are electrically superior to p-type materials. Several groups have reported very high pre- and postprocessing lifetimes in both cast multicrystalline [1], [2] and Czochralski materials [3]. Bothe *et al.* [4] observed a dramatic reduction in bulk lifetime of boron-contaminated oxygen-rich n-type Czochralski silicon wafers that were “switched” to p-type by annihilating oxygen-related thermal donors and pointed out some of the implications for solar cell performance. Researchers have predicted [5] and noted the lifetime stability of phosphorous-doped Czochralski silicon wafers [6] and solar cells made on them [7], in contrast with their boron-doped counterparts. MacDonald and Geerligs [8] and Martinuzzi *et al.* [9] have catalogued electron and hole lifetimes for a variety of chemical impurities, noting the relatively high ratio of hole lifetimes to electron lifetimes and

discussed implications for silicon solar cells. More recently, research groups are reporting good initial solar cell efficiencies on various designs based on various process techniques [3], [10]–[13]. Sanyo [14] and SunPower Inc. [15] have demonstrated efficiencies over 20% on large-area n-type Czochralski and solar-grade float-zoned wafers using vastly different solar cell technologies. There certainly appears to be excellent potential for commercial-grade n-type silicon wafers as a basis for high-efficiency commercial solar cells.

Despite the evidence for using n-type wafers, it is the p-type silicon wafer that dominates the commercial market. With the exception of the two manufacturers noted above, all crystalline silicon solar cell producers use p-type wafers. The main reasons for this are somewhat historical and have their origins over 40 years ago in the early days of commercial silicon solar cell production when space power applications dominated the commercial market. Early work at Bell Laboratories [16], for example, examined the issue of wafer type in the context of space solar cell design. Controlled irradiation studies showed significant degradation of the minority carrier lifetime and junction characteristics, explaining the significant loss of output power over the lifetime of the vehicle. Interestingly, while the solar cells presented in [16] that were fabricated on n-type wafers had a higher beginning-of-life performance, they degraded more when irradiated compared to their p-type counterparts. Since the p-type cells had a superior end-of-life performance, the space industry adopted them for future development and deployment, and subsequently, the terrestrial market has been developed on the basis of the early space solar cell technology.

An argument based purely on mobility has also been used to explain the predominance of p-type silicon wafers in the commercial marketplace. Electrons have a higher mobility compared to holes, by a factor of about 3, and therefore, for the same value of minority carrier lifetime, they have a longer diffusion length. Electrons are the minority carrier in p-type material, and since minority carrier diffusion length is an important material parameter in determining the light-generated current of a silicon wafer, this leads to a preference toward p-type silicon wafers.

Irradiation and mobility arguments, however, are not adequate in the context of high-efficiency commercial silicon solar cells, for a few reasons. The majority of commercial silicon solar cell production today is for use in terrestrial applications, where degradation due to high-energy radiation is not a problem. Further, wafer materials used for high-efficiency commercial silicon solar cells are becoming thin and improving in

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electrical quality to the point that the minority carrier diffusion length is exceeding the thickness of the solar cell. In this case, the light-generated current is dominated more by optics (front reflection control and light trapping) and surface passivation and less by minority carrier mobility.

More importantly, the implicit assumption in the mobility argument that electron and hole lifetimes are equal is not valid when considering inexpensive commercial-grade silicon wafers and high-throughput industrial processes. These materials and processes can contain or introduce a wide variety of defects, including but not limited to chemical impurities, precipitates, complexes, grain boundaries, dislocations, and surfaces. Electron and hole lifetimes for such defects are rarely equal, and as we will show in this paper, this has great implications for the choice of wafer polarity for silicon solar cells.

This raises the main question of this paper: Given defected commercial silicon wafers and industrial process that introduce defects, which is better for silicon solar cells, n-type or p-type silicon wafers? This paper reassesses this question in the context of terrestrial commercial silicon solar cell applications based on the assumption that defects are common in commercial silicon wafers and industrial production.

The paper first details the theoretical link between Shockley–Read–Hall (SRH) defect recombination and solar cell performance, specifically for the case of unequal electron and hole lifetimes, which we herein refer to as asymmetric-SRH (a-SRH) recombination. For the a-SRH case, we illustrate how the recombination rate, and hence, the resulting electrical terminal characteristics of solar cell devices, is strongly dependent on wafer polarity. We next present a case study that examines in detail one specific a-SRH process-induced defect—diffusion-induced misfit dislocations. The recombination characteristics of these defects in both p-type and n-type wafers are characterized with the photoconductance lifetime technique, and the electrical properties of finished solar cells, which were fabricated side-by-side on p-type and n-type silicon wafers, are presented. The comparisons confirm the strong dependence of recombination and device electrical characteristics on wafer polarity. Finally, photoconductance lifetime studies of several industrially relevant situations—process-induced dislocations, surface passivation, and furnace contamination—are presented, further highlighting the importance of wafer polarity in governing the recombination rates in p-type and n-type silicon wafers. The paper concludes that, for the defects presented here, there is a clear bias toward high hole lifetimes and low electron lifetimes. This suggests that given the defected nature of solar-grade silicon wafers and industrial processes, the n-type solar-grade wafers hold a significant advantage over their p-type counterparts.

II. ASYMMETRIC SRH RECOMBINATION AND SOLAR CELL TERMINAL CHARACTERISTICS

Robinson *et al.* [17], Schmidt *et al.* [18], and Cousins *et al.* [19] observed and explained the effect that a-SRH has on passivated emitter rear locally diffused (PERL), random-pyramid PERL (RP-PERL), and double-sided buried contact (DSBC) solar cells, respectively. For an SRH recombination

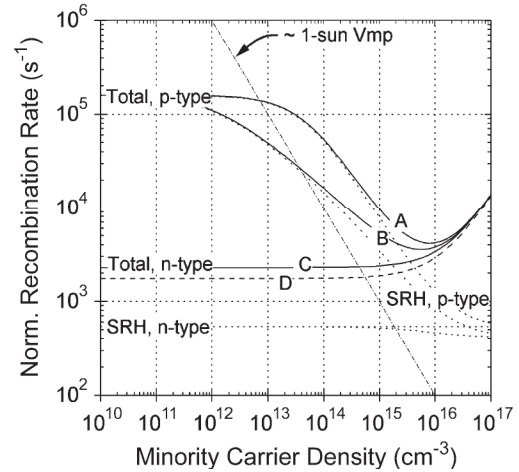


Fig. 1. Simulated total and components of recombination n-type and p-type ($N_a = N_d = 1.5 \times 10^{16} \text{ cm}^{-3}$) silicon wafers, which are expressed as inverse lifetime, including a-SRH recombination ($\tau_p \gg \tau_n$) and emitter recombination ($J_{0e} = 4.8 \times 10^{-14} \text{ A/cm}^2$).

center at one fixed energy, the well-known SRH recombination rate expression is

$$U_t = \frac{(n \cdot p - n_i^2)}{\tau_h \cdot (n + n_1) + \tau_e \cdot (p + p_1)}. \quad (1)$$

Here, τ_h and τ_e are the hole and electron lifetimes, which depend on both the density of defect states and the capture cross sections of electrons and holes. For defects in silicon, hole and electron lifetimes are rarely equal, sometimes being different by several orders of magnitude, which results in a strong dependence of the SRH recombination rates on the excess carrier population. Fig. 1 illustrates several cases by modeling the normalized recombination $U/\Delta n$ for a-SRH recombination ($\tau_h \gg \tau_e$ in all cases) including a small but typical component of emitter recombination in each case. Curve A shows the total recombination in a p-type wafer with simple (i.e., traps at a single energy level) a-SRH recombination. Curve B shows the total recombination in a p-type wafer with a more realistic a-SRH recombination (traps distributed over a spectrum of energy levels). Curve C shows the total recombination in an n-type wafer for both types of a-SRH used for curves A and B, and curve D shows the total recombination without any a-SRH recombination (emitter recombination only), which represents the “unaffected” case.

Except for the omission of junction recombination, which occurs at the cleaved edge of the device [20], Fig. 1 is fairly typical of high-efficiency DSBC solar cells made at the University of New South Wales (UNSW). The SRH recombination rate is dominated by the minority carrier lifetime at low injection levels and by the sum of minority and majority carrier lifetimes at higher injection levels. It is important to note that the transition between these two regimes can occur at or above the one-sun operating point of a silicon solar cell, where it has a significant negative impact on the terminal characteristics of solar cell devices. The dot-dash line in Fig. 1 labeled “1-sun Vmp” highlights this key point. This line shows the locus of operating points for a high-efficiency silicon solar cell,

assuming a thickness of $250\ \mu\text{m}$, a light-generated current of $40\ \text{mA}/\text{cm}^2$, and an operating-point injection level that is about 10% of the open-circuit operating-point injection level. This line is calculated using

$$\begin{aligned}\frac{U_{\text{mp}}}{\Delta n_{\text{mp}}} &\approx 0.1 \cdot \frac{U_{\text{oc}}}{\Delta n_{\text{oc}}} \\ &= 0.1 \cdot \frac{G_{\text{oc}}}{\Delta n_{\text{oc}}} \\ &= 0.1 \cdot \frac{J_{\text{lg}}}{q \cdot W \cdot \Delta n_{\text{oc}}}.\end{aligned}\quad (2)$$

Here, $U_{\text{mp}}/\Delta n_{\text{mp}}$ is approximately the normalized recombination at the one-sun maximum power-point injection level Δn_{mp} . $U_{\text{oc}}/\Delta n_{\text{oc}}$ is the normalized recombination at the one-sun open-circuit injection level Δn_{oc} , at which point generation G_{oc} and recombination U_{oc} are equal, and J_{lg} and W are the assumed light-generated current and device thickness, respectively. The full impact of a-SRH recombination is revealed when the simulation presented in Fig. 1 is viewed along this locus of operating points (as opposed to comparing the simulations at a single arbitrary injection level). The normalized recombination is different by as much as two orders of magnitude, and the p-type solar cell operates at an injection level that is between one and two orders of magnitude lower than the n-type solar cell. This is roughly equivalent to a difference of as much as two orders of magnitude in the effective lifetime, or a difference of between 60 and 120 mV at the operating point of the solar cell.

The simulation data in Fig. 1 can be recast as implied current-voltage (I - V) curves to illustrate this key point, using

$$V_i = \frac{k \cdot T}{q} \ln \left(\frac{n \cdot p}{n_i^2} \right) \quad (3)$$

and

$$J_i = q \cdot W \cdot (U_t + U_e) \quad (4)$$

where V_i and J_i are the implied voltage and implied current density, U_t and U_e are the SRH and emitter recombination rates, and W is the device thickness. Fig. 2(a) shows the resulting implied dark current density-voltage ($\log(J_i)$ - V_i) and implied local ideality factor curves (m_i - V_i). Fig. 2(b) shows an implied illuminated I - V curve, assuming a constant value for light-generated current density ($J_{\text{lg}} = 40\ \text{mA}/\text{cm}^2$). The influence of the a-SRH recombination process on the terminal characteristics of a solar cell can be seen clearly in these figures. The recombination manifests itself as a characteristic shift to higher voltage at higher current in the dark $\log(J_i)$ - V_i curves, a “hump” in the dark m_i - V_i curves, and a soft fill factor in the lighted implied I - V curves. It can also be observed in Fig. 2(b) that the voltage reduction at the operating point corresponds well with the observations regarding Fig. 1. Curve A shows a loss of about 120 mV, curve B shows a loss of a little less than 60 mV, and curve C is hardly degraded compared to the “unaffected” curve D.

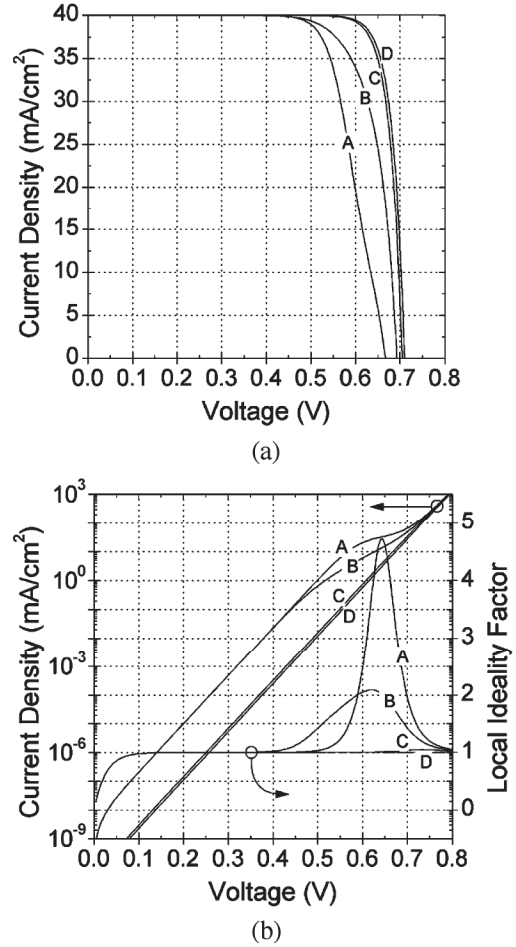


Fig. 2. (a) Resulting dark $\log(J)$ - V and dark m - V curves. (b) Lighted J - V curves for the cases presented in Fig. 1.

Comparison of curves A-D in Fig. 2(b) clearly shows the negative impact that a-SRH recombination can have on the terminal electrical characteristics of a solar cell, but more importantly, it illustrates the difference that wafer type makes in terms of mitigating this type of recombination. For this case, where $\tau_p \gg \tau_n$, the p-type solar cell is adversely affected (curves A and B) compared to the “unaffected” case (curve D), whereas the n-type solar cell is hardly affected (curve C). It should be noted that the converse is true. For the case of $\tau_p \ll \tau_n$, the p-type material would be superior. However, as we will show in the following sections, there is growing evidence of a bias among the various types of defects common to silicon solar cells toward low electron lifetimes and high hole lifetimes.

III. CASE STUDY—MISFIT DISLOCATIONS AND THE DSBC SOLAR CELL

Perhaps one of the best experimental demonstrations of the link between defect considerations and solar cell performance, as it relates to the a-SRH argument outlined in the previous section, is that of boron diffusions in high-efficiency buried contact (BC) solar cells. DSBC solar cells fabricated on p-type substrates suffer from poor fill factor, and a characteristic hump in the m - V curve that was initially attributed to floating junction shunting [21]. McIntosh [20] first demonstrated that the heavy

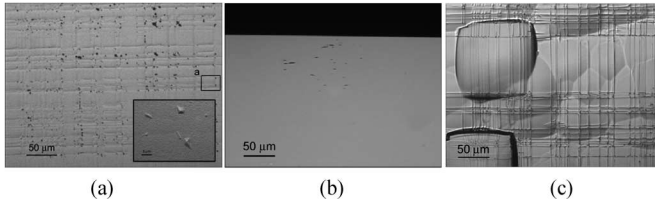


Fig. 3. Photo of the misfit dislocation networks observed for phosphorus and boron diffusions as revealed by Yang etching. (a) Heavy boron diffusion, observed on the plan view, (100) surface. (b) Heavy boron diffusion, observed on the cross section, (110) surface cross section. (c) Heavy phosphorus diffusion, observed on the plan view, (100) surface.

boron groove diffusion, and not the floating junction shunting, was responsible for the decrease in fill factor. Following this work, Cousins and Cotter [22] identified boron diffusion-induced misfit dislocations as the specific a-SRH recombination center responsible for the poor performance. Guo [23], working in parallel on n-type high-efficiency interdigitated backside BC (IBBC) solar cells and using identical boron groove diffusions, first pointed out the absence of the deleterious effects of a-SRH recombination in working solar cells using J - V and m - V analysis.

Misfit dislocations form due to stress gradients that arise from dopant concentration gradients, such as those typically found in solid-state diffusions. Stress on the silicon lattice is caused by atomic radius mismatch between silicon and the dopant atom (the covalent radii of boron and phosphorus are 0.88 Å and 1.06 Å, respectively, compared with 1.18 Å for silicon), resulting in a localized contraction of the silicon lattice around the substitutional dopant atoms. For low concentrations of dopant atoms, the lattice accommodates this stress elastically. When the concentration of dopants exceeds a critical concentration, the lattice can no longer accommodate elastically, and misfit dislocations are generated. These diffusion-induced misfit dislocations are half-loop dislocations nucleated at the diffusion surface in the $\langle 110 \rangle$ directions, consisting of two screw dislocations perpendicular to the diffusion surface and an edge dislocation line parallel to the diffusion surface in the $\langle 110 \rangle$ direction. At diffusion temperatures, the two screw dislocations glide out of the wafer's edge within seconds, and the edge dislocation lines glide into the substrate in response to the stress gradient governed by the diffusion profile. The collision of several edge dislocations forms a cross-hatch dislocation network characteristic of diffusion-induced misfit dislocations [24]. Fig. 3 shows the characteristic cross-hatch pattern that results from Yang defect etching ($\text{CrO}_3 : \text{HF}$) [25] of the surfaces and cross sections of heavy boron and phosphorus diffusions typically used in the fabrication of DSBC solar cells [22].

Fig. 4(a) shows the typical recombination characteristics for a heavy boron diffusion—known to produce the misfit dislocation networks shown in Fig. 3—on p-type and n-type silicon test wafers. Fig. 4(b) shows a similar plot of lightly boron-diffused p-type and n-type silicon wafers known to not produce dislocation networks. The correlation between the boron process (heavy or light), the misfit dislocation (present or absent), and the a-SRH recombination (present or absent) is reasonably well established—Cousins and Cotter [22] provide more detail for both phosphorus and boron diffusions. The key observations to

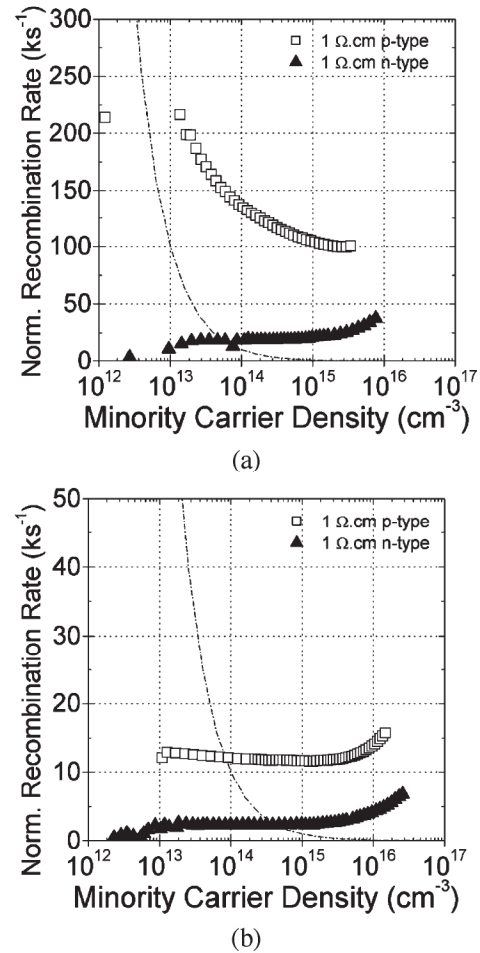


Fig. 4. Photoconductance measurements of inverse lifetime for diffusions in p-type and n-type float-zoned (FZ) silicon, demonstrating the presence or absence of a-SRH resulting from (a) heavy boron diffusions ($\sim 20 \Omega/\text{sq}$) known to produce a misfit dislocation network (as per Fig. 3) and (b) light well-controlled boron diffusion ($\sim 100 \Omega/\text{sq}$) known to be free of a diffusion-induced misfit dislocation network. The dash-dot line shows the approximate one-sun operating point for a high-efficiency solar cell.

make in the graphs in Fig. 4 are the reduced overall recombination in n-type wafers and the absence of the strong a-SRH behavior for the boron diffusions made on the n-type wafers. This occurs because hole lifetimes are significantly greater than electron lifetimes for these particular defects.

The DSBC solar cell design, which is shown in Fig. 5, is ideal for making a direct comparison of solar cell terminal characteristics of solar cells made side-by-side on n-type and p-type silicon wafers. The DSBC processing sequence can be applied to either p-type or n-type wafers without significant changes in the processing sequence—diffusions, oxidations, and even metallization processes can be applied with good effect to both types of wafers processed in split batches. Furthermore, the heavy boron diffusion characterized in Figs. 3(a) and 4(a) is typical of the heavy boron diffusion process used in the p++ contact diffusion formed on the groove walls of both types of DSBC solar cell. Fig. 6 shows a comparison of terminal characteristics of p-type and n-type DSBC solar cells that were fabricated using the nearly identical fabrication sequences and processed in a split batch.

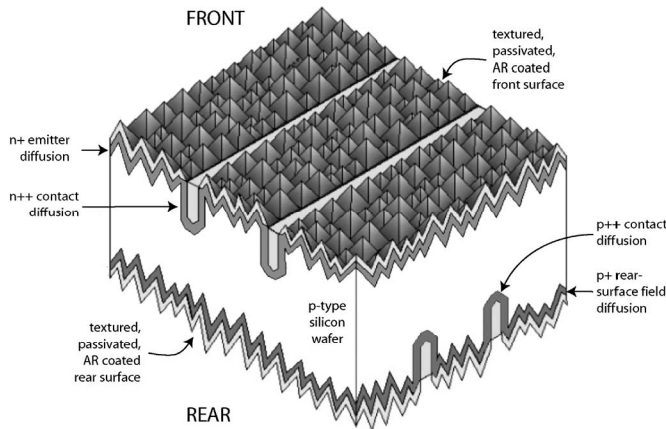
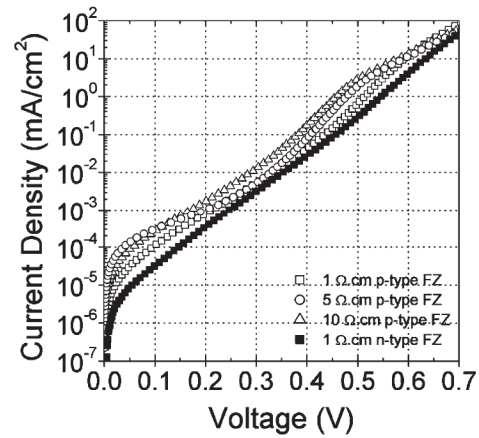


Fig. 5. DSBC solar cell design on a p-type silicon wafer. By reversing the polarity of all diffused regions, the DSBC solar cell can be realized on an n-type silicon wafer.

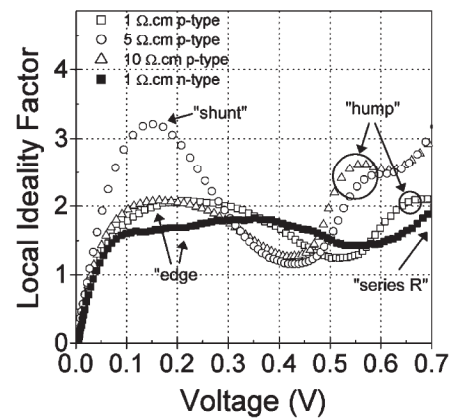
The characteristic behavior of a-SRH recombination attributed by Cousins and Cotter [22] to boron-diffusion-induced misfit dislocations is apparent in the terminal characteristics of all three p-type solar cells, although the effect is most clearly demonstrated in the local ideality (m - V) curves shown in Fig. 6(b). Before discussing the relevant features in these curves, several other features commonly found in the m - V curves that are not relevant to the current discussion should be pointed out. At low voltages, an ohmic shunt can be seen in one of the p-type solar cells, whereas the other three solar cells exhibit edge-induced junction recombination because of their relatively large perimeter compared to their area [20]. At high voltages, all four solar cells exhibit series resistance. What is most relevant is that all three p-type devices show the hump that is characteristic of the a-SRH recombination process induced by heavy boron groove diffusions and that the n-type solar cell does not exhibit the hump. All four solar cells used boron groove diffusions that are known to introduce diffusion-induced misfit dislocations, yet, only the p-type solar cells are affected by their presence.

The peak voltage at which the hump occurs in the m - V curves, which is shown in Fig. 6(b), shifts with wafer resistivity, as expected from SRH recombination statistics [19]. The exact voltage of the peaks of the humps is difficult to correlate to the wafer doping level, however, because the peaks are obscured somewhat by series resistance effects. More importantly, the hump, which is attributed to the transition in the a-SRH recombination statistics as described in the previous section, occurs roughly around the operating point of the solar cell, where it adversely affects all of the key terminal characteristics of the p-type solar cells, especially at the operating point, as can be seen in Fig. 6(c), but not the n-type solar cells.

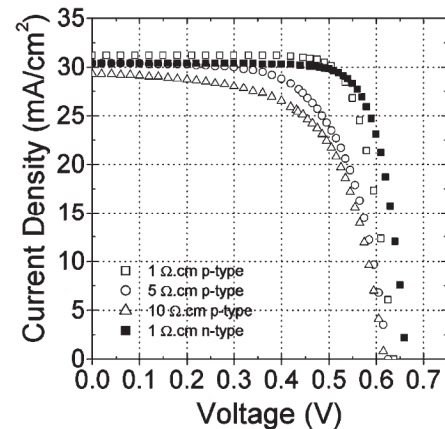
The case of the $1\text{-}\Omega\cdot\text{cm}$ p-type and $1\text{-}\Omega\cdot\text{cm}$ n-type solar cells deserves extra discussion. While the fill factor of both solar cells looks comparable, the detrimental effect of a-SRH recombination on the p-type solar cell is not immediately apparent by examining the fill factor alone. In the $1\text{-}\Omega\cdot\text{cm}$ p-type solar cell, the transition injection level in the SRH statistics occurs at around 675 mV [note the peak of the associated hump in Fig. 6(b)], which is well above the open-circuit voltage of this



(a)



(b)



(c)

Fig. 6. Dark $\ln(J)$ - V , dark m - V , and lighted J - V curves of a split batch of DSBC solar cells made on various p-type and n-type silicon substrates.

solar cell. However, the voltage characteristics of this solar cell are degraded by a-SRH recombination, because even at open-circuit voltage, the solar cell operates in the regime where the a-SRH recombination is dominated by the short electron lifetimes. The open-circuit voltage of the p-type solar cell is 20 mV lower than its n-type counterpart, yet, based on the relative doping levels (the p-type wafer has a factor of three higher doping level), one would expect the p-type solar cell to reach open-circuit voltages about 25 mV higher than the n-type solar cell.

IV. OTHER INDUSTRIALLY RELEVANT CASES

The discussion in Section III provides a good basis for answering the p-versus-n question; however, the diffusion-induced misfit dislocation is only one entry in the catalogue of SRH recombination centers. The p-versus-n question depends on the nature and density of SRH defects that are inherent in commercial silicon wafers and processes. Clearly, with ultra-high-purity float-zoned silicon wafers and a controlled laboratory environment, it is possible to almost completely avoid the deleterious effects of a-SRH recombination and fabricate defect-free high-efficiency silicon solar cells. This has been demonstrated at UNSW with the 24.7% efficient PERL cells [26]. However, solar-grade wafers and high-volume low-cost manufacturing processes do not have the same wafer quality and process control. Multicrystalline silicon wafers are riddled with a diverse population of chemical impurities and complexes, dislocations and stacking faults, twins and grain boundaries, and surfaces.¹ Industrial processes can subject a wafer to intrinsic and extrinsic stresses, scratches, contamination, and imperfectly passivated surfaces that contribute further to population of defects. More information is needed about the nature of defects common to silicon solar cells.

MacDonald and Geerligs [8] and Martinuzzi *et al.* [9] have investigated the nature and significance of chemical impurities commonly found in multicrystalline silicon wafers. Many of the usual suspects—Fe, Ti, V, Cr, Mo, Co, FeB, and CrB—show asymmetric capture cross sections with high hole lifetimes and low electron lifetimes, although some do not. As far as these elements are concerned, using n-type instead of p-type wafers has good potential to mitigate the SRH recombination associated with these defects.

This section looks at the nature of a few other defects that are relevant to the industrial manufacture of silicon solar cells—dislocations, surfaces, and furnace contamination—with the aim of providing additional insight into the p-versus-n question.

A. Laser-Induced Dislocations

Dislocations can be induced by any number of industrial process steps that place the silicon wafer under stress. Furnace loading and unloading [27], oxidation of textured surfaces [28], and laser ablation [29] can induce stresses sufficient to induce local dislocations that can glide a considerable distance during subsequent thermal treatments. The DSBC and IBBC process sequences use laser ablation, so the impact of laser-induced dislocations is of importance to these types of solar cells. Here, we look the recombination statistics of laser-induced dislocations in p-type and n-type wafers and generalize to dislocations generated by other processes.

The laser ablation process is used to make the grooves of DSBC and IBBC solar cells. The silicon wafer is heated in a local area above the vaporization temperature of silicon in a very short time (a few hundred nanoseconds). The molten silicon is ejected from the wafer, leaving a groove behind the

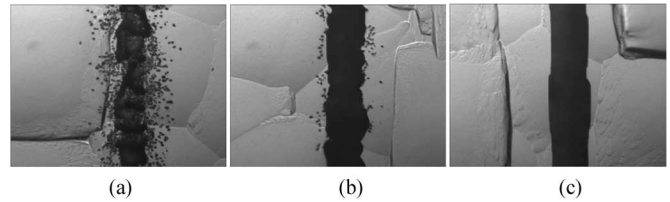


Fig. 7. Intentionally induced dislocations on laser-grooved samples that were sodium-hydroxide-etched and then subjected to a thermal cycle. (a) 0-min etch. (b) 12-min etch. (c) 20-min etch.

path of the laser. The ablation process creates a thin layer of damage on the walls of the groove that is normally removed using a sodium hydroxide etch. If the damaged layer is not removed properly, these dislocations will glide into the bulk of the wafer during subsequent thermal processes [29].

A typical front electrode grid was laser-scribed into a split batch of p-type and n-type silicon wafers that were subsequently sodium-hydroxide-etched for different times and then subjected to a thermal treatment at 1000 °C for 2 h in an inert ambient. A Yang etch was used to delineate the dislocations, which are clearly visible in Fig. 7(a) and (b), but not in Fig. 7(c). The sample shown in Fig. 7(c) was sufficiently etched to remove the damage layer, thereby avoiding the formation and propagation of dislocations during the thermal treatment step.

A second split batch of p-type and n-type wafers was processed identically and then phosphorus-diffused and oxidized to provide a high-quality surface passivation. The finished wafers were then characterized using the photoconductance lifetime technique. The data are shown in Fig. 8.

The difference in the recombination statistics of the p-type and n-type samples is remarkable. The n-type wafers are nearly completely insensitive to the presence of the dislocations, supporting very low recombination rates even for the worst case. The p-type wafers are highly sensitive and show higher recombination and a strong a-SRH effect, the full impact of which is masked by the depletion region modulation effect [30], [31] at injection levels below about 10^{13} cm^{-3} .

The misfit- and laser-induced dislocations both show high hole lifetimes and low electron lifetimes, and it is reasonable to expect that dislocations induced by other processes would behave similarly. Therefore, for materials and processes where dislocations might be present or introduced (for example, multicrystalline silicon wafers or rapid furnace loading and unloading processes), the n-type wafer has a clear advantage in terms mitigating the associated recombination.

B. Wafer Surfaces

Surfaces are a well-studied source of recombination in silicon solar cells. The ratio of hole to electron lifetimes is already known to be much greater than one for silicon surface states passivated by both silicon dioxide and silicon nitride [32]. We confirm this understanding again here in order to draw attention to the importance considering surface recombination when addressing the p-versus-n question.

The graphs in Fig. 9 show the recombination statistics for three cases of p-type and n-type surfaces prepared and measured at UNSW using the photoconductance lifetime technique:

¹The annual *Proceedings of the NREL Workshop on Crystalline Silicon Solar Cells* documents extensive studies of the role of defects in silicon and other photovoltaic materials and devices.

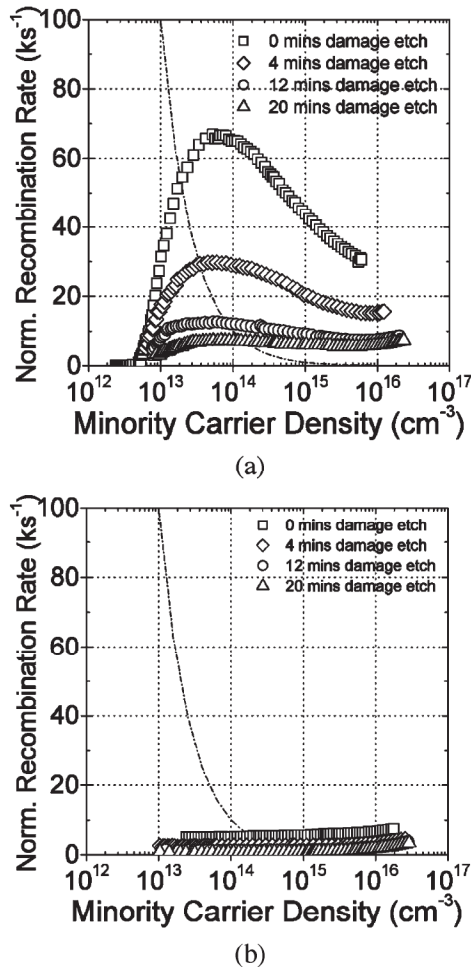


Fig. 8. Photoconductance measurements of the laser-scribed wafers showing (a) dominance of the a-SRH recombination in the p-type samples and (b) absence of a-SRH recombination in the n-type samples. The dash-dot line shows the approximate one-sun operating point for a high-efficiency solar cell.

(a) direct passivation by thermally grown silicon dioxide; (b) direct passivation by plasma-enhanced chemical vapor deposition (PECVD) silicon nitride; and (c) passivation by PECVD silicon nitride of boron and phosphorus diffused surfaces. The graphs show that in all cases, the ratio of hole lifetimes to electron lifetimes is greater than one. Thus, as far as silicon surfaces are concerned, the n-type surface has a clear advantage in terms of mitigating the associated recombination.

C. Contamination

Wafer contamination is a spurious problem that greatly reduces wafer lifetime and degrades solar cell performance. The list of sources of chemical contaminants is endless—poor quality of water, poor handling, furnace cross contamination, particles from clothing and hair, etc. Clean room facilities and procedures go a long way to solving contamination problems, in fact, PERL silicon solar cells routinely achieve $> 24\%$ in quite rudimentary clean facilities.

Despite our best efforts, diffusion and oxidation furnaces at UNSW occasionally become contaminated by unknown chemical impurities. One particular split batch of three $1\text{-}\Omega \cdot \text{cm}$ p-type and three $1\text{-}\Omega \cdot \text{cm}$ n-type float-zoned solar cells was

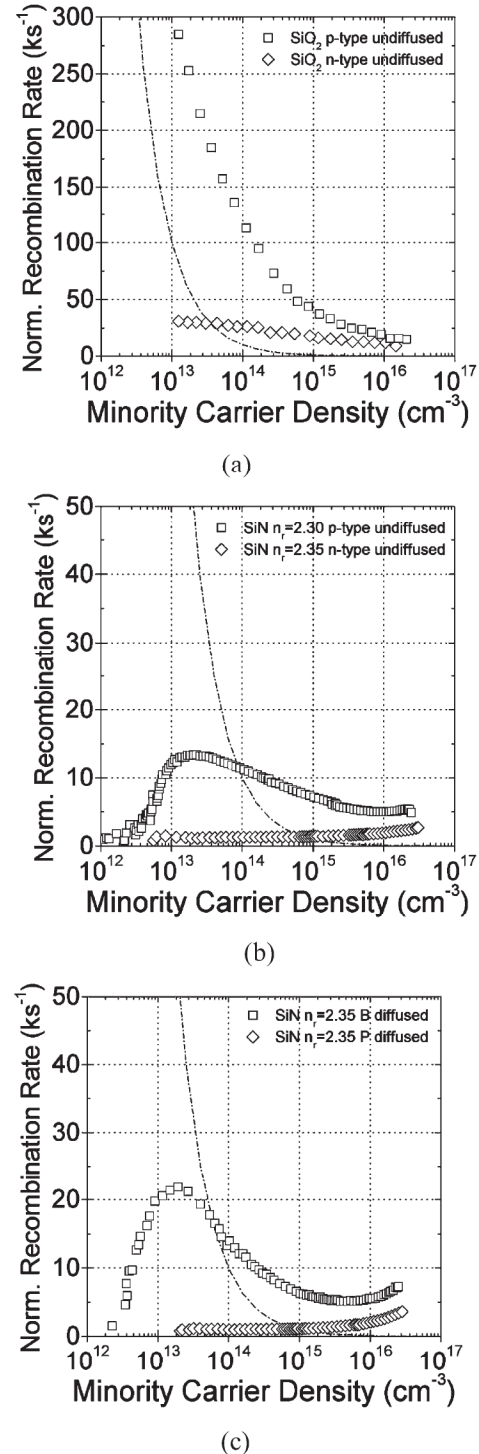


Fig. 9. Photoconductance measurements of surface recombination in p-type and n-type FZ silicon wafers. (a) Direct passivation of $1\text{-}\Omega \cdot \text{cm}$ p-type and n-type wafers with thermally grown silicon dioxide. (b) Direct passivation of $1\text{-}\Omega \cdot \text{cm}$ p-type and n-type wafers with PECVD silicon nitride. (c) Passivation of light phosphorus and boron diffusions ($\sim 100 \text{ }\Omega/\text{sq}$) on a $1\text{-}\Omega \cdot \text{cm}$ n-type silicon wafer with PECVD silicon nitride. The dash-dot line shows the approximate one-sun operating point for a high-efficiency solar cell.

rejected after phosphorus diffusion and oxidation due to an unexpected contamination that was detected by routine photoconductance lifetime monitoring. Fig. 10 shows the recombination characteristics measured using the photoconductance lifetime technique. The variability in the recombination

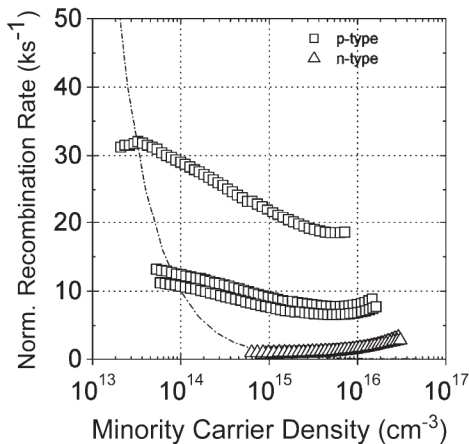


Fig. 10. Photoconductance measurements of p-type and n-type silicon wafers unintentionally contaminated during a phosphorus diffusion and thermal oxidation process sequence. The dash-dot line shows the approximate one-sun operating point for a high-efficiency solar cell.

statistics of the p-type samples is consistent with this type of contamination problem. The important things to note are the tight distribution of the recombination statistics for the three n-type wafers (the three curves overlap to within the width of the border of the symbols used in the graph), the much lower overall recombination for the n-type wafers and the absence of a strong a-SRH behavior in the curves. This strongly suggests that the n-type wafers are largely unaffected by this particular contamination problem in sharp contrast to the p-type wafers. It is therefore concluded that for this particular contamination problem, n-type silicon wafers have clear advantage in terms of mitigating the recombination associated with contamination.

V. CONCLUSION

N-type silicon wafers offer a significant opportunity for commercial high-efficiency silicon solar cells. Recombination and device characteristics have been proven to be stable under illumination. High lifetimes have been reported in multicrystalline, Czochralski, and float-zoned wafers, and high efficiency solar cells are now being reported in solar cells made on n-type wafers. As for feedstock considerations, the growing list of defects that exhibit high hole lifetime and low electron lifetime, and the impact that the associated a-SRH recombination has on the terminal characteristics of solar cells, suggests that n-type silicon wafers are better suited for high-efficiency commercial silicon solar cells. As for industrial manufacturing processes, the excellent tolerance of n-type wafers to induced or introduced defects suggest the same again. Overall, in terms of the electrical requirements of a solar-grade wafer for industrial high-efficiency silicon solar cells, n-type wafers seem to hold a significant advantage over p-type wafers.

Issues in the broader context of the p-versus-n question do not seem terrible. n-type wafers are not significantly more expensive than p-type wafers. Module manufacturing technology should cope with n-type solar cells, and system integrators should have no problem with n-type modules. Perhaps the largest issues are diffusion technology (specifically forming the p+ emitter), metallization technology and the relatively large

segregation of phosphorus that leads variations in doping during crystal growth. Boron diffusion, which is more difficult than phosphorus diffusion, is not impossible with a little care, and good results with printed and plated metallization are already being reported. The tolerance to variations in wafer doping will require some careful attention. New device concepts and designs based on n-type solar cells are already springing up. Given the demonstrated potential, n-type silicon wafers are an opportunity for high-efficiency commercial silicon solar cells that is not to be overlooked.

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