Analysis of the interdigitated back contact solar cells: The n-type substrate lifetime and wafer thickness*

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The n-type silicon integrated-back contact (IBC) solar cell has attracted much attention due to its high efficiency, whereas its performance is very sensitive to the wafer of low quality or the contamination during high temperature fabrication processing, which leads to low bulk lifetime τ_{bulk}. In order to clarify the influence of bulk lifetime on cell characteristics, two-dimensional (2D) TCAD simulation, combined with our experimental data, is used to simulate the cell performances, with the wafer thickness scaled down under various τ_{bulk} conditions. The modeling results show that for the IBC solar cell with high τ_{bulk}, (such as 1 ms–2 ms), its open-circuit voltage V_{oc} almost remains unchanged, and the short-circuit current density J_{sc} monotonically decreases as the wafer thickness scales down. In comparison, for the solar cell with low τ_{bulk} (for instance, < 500 μs) wafer or the wafer contaminated during device processing, the V_{oc} increases monotonically but the J_{sc} first increases to a maximum value and then drops off as the wafer's thickness decreases. A model combing the light absorption and the minority carrier diffusion is used to explain this phenomenon. The research results show that for the wafer with thinner thickness and high bulk lifetime, the good light trapping technology must be developed to offset the decrease in J_{sc}.

Keywords: lifetime, wafer thickness, interdigitated back contact solar cells, technology computer-aided design

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1. Introduction

For the silicon solar cells, pursuing higher energy conversion efficiency on thinner Si wafer is the future development trend for the photovoltaic industry.[1] Hence, the interdigitated-back contact (IBC) solar cell based on n-type Si wafer has attracted extensive attention due to its high efficiency of up to 24%, as realized in the large area 125 mm×125 mm.[2] The absence of the front metal contacts of IBC solar cell allows the full light illumination without any shading loss. On the back side of the cell, there are p^+-emitter, n^+-base and metallization contacts, which require the complex fabrication processing including several mask and alignment steps, high temperature oxidation and diffusion processes, such as boron (B) and phosphorus (P) diffusion.[3] For IBC structure, the photon-generated carriers need to transport through the whole thickness of wafer and then separate and collect by the p^+-emitter and n^+-base on the back side of the cell. Generally, in order to obtain high conversion efficiency, the diffusion length of the minority carriers should be at least four times the thickness value of the cell.[4,5] However, as is well known, the n-Si wafer with high τ_{bulk} (> 1 ms) and good surface passivation, i.e., the low surface recombination velocity s_{eff} (SRV), can be easily degraded during the above-mentioned complex fabrication processing. For example, for the high temperature oxidation (> 950 °C) and boron diffusion (> 1000 ° C), if there is contamination during the processing, then the recombination center can be activated and the bulk lifetime can be greatly degraded in a time range from millisecond to several microseconds. Even for the surface recombination velocity s_{eff} is very low, the photon-generated carriers, which transport from the wafer's front surface to the back, can extensively recombine via those bulk centers due to contaminations. Recently, it was found that if careful fabrication process is not controlled, then oxidation induced stacking faults (OSFs) can form during the high temperature fabrication processing, which obviously reduces the final τ_{bulk} of n-Si wafer.[6] Thus, the measured effective minority lifetime τ_{eff}, which generally includes τ_{bulk} and surface lifetime τ_{surf} (equal to wafer thickness SRV divided by W), is very low even if the τ_{surf} is high. Hence, the fabrication processing such as n-Si wafer cleaning, surface passivation and boron & phosphorous diffusion should be handled very carefully. But to date, to our knowledge, there are no systematic research reports on the influence of n-Si wafer's τ_{bulk} degradation on the characteristic of IBC solar cell. Accordingly, it is necessary to clarify the

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influence of τ_{bulk} change on the performance of IBC solar cell when the wafer thickness scales down.

In this paper, combining with our experimental data, we systematically study the effect of change in bulk lifetime on the property of IBC solar cell when the wafer thickness scales down by using 2D technology computer aided design software (2D TCAD),[7] which is widely used in solar cell simulation.[8] During the simulation, in order to highlight the effect of bulk lifetime on the device property, we assume that the whole IBC solar cell has good front and back surface passivation with SRV $S = 10$ cm/s (in fact, this can be obtained by good Al_2O_3 or SiO_2 passivation).[9] Based on the results of the 2D TCAD simulation, the key factors are discussed and clarified for the n-Si IBC solar cell with scaling down the thickness. It is helpful for fabricating the future cost-effective IBC solar cell of high efficiency with using the thinner wafer.

2. Experiment

In this work, we will first investigate the influence of high temperature process on lifetime. The n-type FZ ⟨100⟩ silicon wafers with 5 Ω·cm resistivity were cleaned using the standard RCA procedure.[10] Then, we divided all of the wafers into five groups with different process listed in Table 1. After all of the processes, Semilab PV2000A was used to determine lifetime. From the results, we could find that the τ_{eff} values of groups 1 and 2 (without high temperature process) both excess 1 ms after passivation. Al_2O_3/SiN_x double passivation was more effective than SiN_x passivation for n-type silicon due to field effect passivation.[9] Group 3 was processed in oxygen ambient using a conventional quartz furnace, and a 23-nm SiO_2 layer was achieved under the condition of 950 °C and 30 min. Then, we removed the oxide layer by dilute HF, and a new SiN_x layer was deposited by PECVD for passivation. Compared with group 2, the τ_{eff} is much lower than that of group 3, which was subjected to an extra thermal oxidation process. In order to exclude the effect of silicon surface defect on τ_{bulk}, group 4 experienced the same process as group 3 except inserting additional KOH etch between HF dip and SiN_x deposition. An unexpected result was achieved, the τ_{eff} of group 4 was only 30 μs which was much lower than τ_{eff} of group 3. A possible reason was that the residual K^+ ion moved from surface into the inside of silicon in the PECVD SiN_x process (300 °C). Therefore, SC-2 solution ($HCl:H_2O_2$:DI water = 1:1:6) was used to remove the K^+ ion in group 5. The τ_{eff} of group 5 after all processes was 140 μs, this value was similar to the τ_{eff} of group 3 and proved that the high temperature oxidization process leads to the decrease of τ_{eff}. The same problem appears in other high temperature processes, such as boron and phosphorus diffusion, which cannot be avoided in traditional production process of solar cells. From group 1, we verified that the τ_{bulk} of our substrate exceeded 1926 μs. Therefore, τ_{eff} (1323 μs) was mainly determined by τ_{surf} for SiN_x passivation in group 2. For group 5, the wafers were also passivated by SiN_x but suffered oxidation process in contrast to group 2, τ_{eff} was determined by τ_{bulk}. Consequently, τ_{bulk} decreases from 1926 μs (at least) to 140 μs due to the high temperature process. In the next section, we will add these experimental results to our simulation to investigate the influence of high temperature process on the performance of an IBC solar cell.

Table 1. All wafers with different processes.

Group	Process	τ_{eff}/μs
1	ALD 20-nm Al_2O_3 + SiN_x[a]	1926
2	SiN_x	1323
3	Oxidization[b] + HF + SiN_x	193
4	Oxidization + HF + KOH + SiN_x	30
5	Oxidization + HF + KOH + SC-2[c] + SiN_x	140

[a] Plasma-enhanced chemical vapor deposition 80-nm SiN_x.
[b] 950 °C 30 min in dry oxygen ambient.
[c] $HCl:H_2O_2$:DI water = 1:1:6 (80 °C; 15 min) + dilute HF + DI water.

3. Simulation and discussion

The 2D TCAD tool is used to simulate the operation of IBC solar cells when τ_{bulk} decreases. As a pathway to reducing the dependence of IBC solar cells on τ_{bulk}, reducing the variation of wafer thickness with τ_{bulk} is also simulated. The investigated device structure is shown in Fig. 1 in which the back emitter, the back surface field (BSF), and the front surface field (FSF) are formed by ion implantation. Implant energy and implant dose are given in Table 1. The simulated region is defined between the centre of two neighboring contacts of emitter and base. The widths of emitter and BSF are fixed to be 1700 μm and 300 μm, respectively. The gap between emitter and BSF is defined to be 50 μm to reduce the shunt current. To improve the light absorption, a two-layer (SiO_2/SiN_x) AR coating is used on the front side of device. In order to accurately simulate the IBC solar cells, the effects including carrier concentration dependent SRH recombination, Auger recombination, carrier concentration dependent mobility, band-gap narrowing are taken into account in the model. Moreover, the

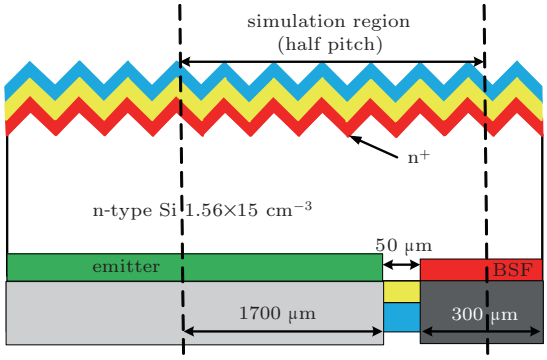


Fig. 1. (color online) Schematic view of the simulated structure of IBC solar cell.

Fermi–Dirac statistics are used to simplify the calculation. Since we focus on the effect of wafer thickness variation on the performance of IBC solar cells, the recombination rate of the front surface and back surface is 10 cm/s for assuming excellent passivation. In the model, the doping concentration of N-type silicon wafer is defined to be 1.56×10^{15} cm^{-3}as commonly used for solar cell application. Devices with wafer thickness values changing from 300 μm to 50 μm for various lifetimes are simulated and the main parameters used in the model are listed in Table 2.

Table 2. Parameters used in simulation.

Substrate	
Doping type	n
Doping concentration	1.56×10^{15}/cm^{-3}
Thickness	250 μm
Surface recombination	
S_{front}	10 cm/s
S_{back}	10 cm/s
Impurity doping	
Implant dose of emitter	3×10^{15}/cm^{-2}
Implant energy of emitter	90 keV
Implant dose of BSF	1×10^{15} cm^{-2}
Implant energy of BSF	150 keV
Implant dose of FSF	2×10^{13} cm^{-2}
Implant energy of FSF	20 keV
Antireflection layer	
Refractive index of SiO_x	1.5
Thickness of SiO_x	105 nm
Refractive index of SiN_x	2.6
Thickness of SiN_x	55 nm
Measurement	
Spectrum	AM 1.5G
Incidence angle	90°
Testing voltage	0 ∼ 0.75 V

Figure 2(a) shows the dependences of V_{oc} of IBC solar cells on wafer thickness with τ_{bulk} decreasing. It can be clearly seen from the figure that V_{oc} is not affected by wafer thickness for the substrate with high τ_{bulk}. However, V_{oc} drops off considerably with increasing wafer thickness when the τ_{bulk} becomes low. This phenomenon can be explained by one ideal-diode model as given by[11]

$$V_{oc} = (kT/q)\ln(pN_D/n_i^2), \quad (1)$$

where N_D, n_i, p are the doping concentration of the substrate, the intrinsic carrier concentration, and the injected hole concentration in emitter region, respectively; k is Boltzmann's constant; T is absolute temperature; and, q is the charge on an electron. For the substrate with low τ_{bulk}, the hole generated on the front side of device can be easily lost due to the large SRH recombination. Therefore, for the thicker substrate, few holes can reach the emitter, resulting in the lower value of V_{oc}.

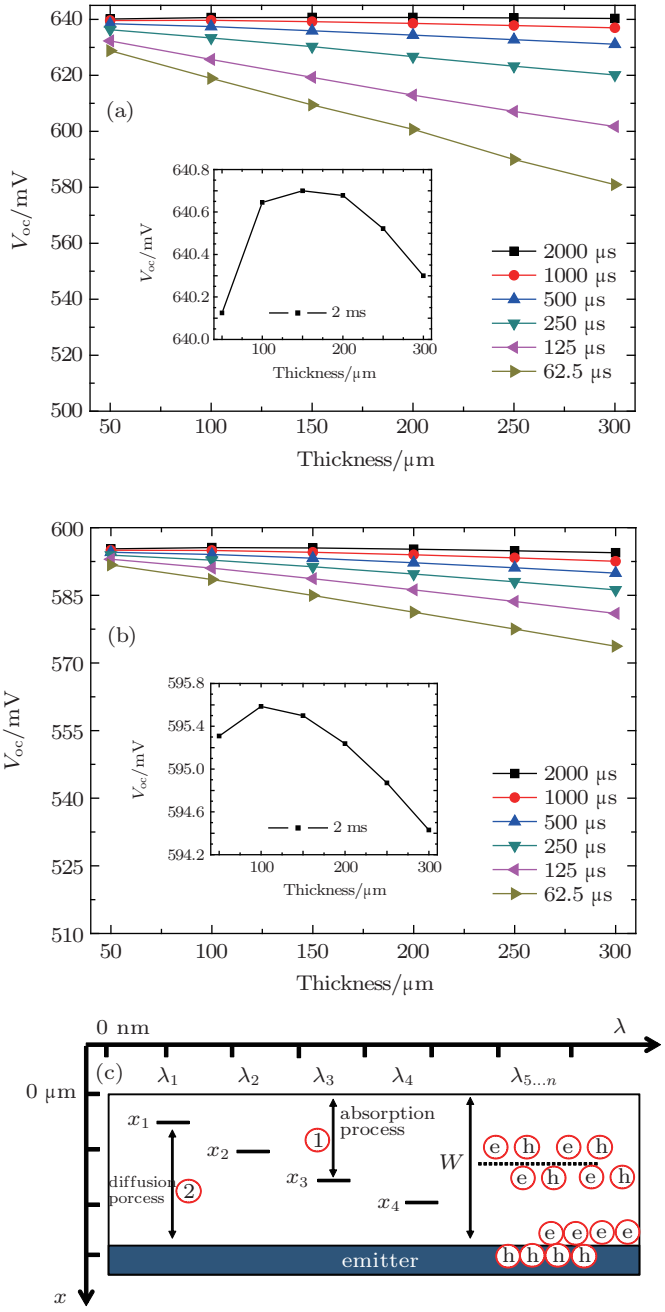


Fig. 2. (color online) Variations of open-circuit voltage with wafer thickness for various bulk lifetimes, calculated by (a) the TCAD model of IBC solar cells, and (b) simple model of hole generation and diffusion. (c) Process of generation and diffusion of holes.

The inset of Fig. 2(a) shows the V_{oc} as a function of wafer thickness with the τ_{bulk} value of 2 ms. It can be seen that the value of V_{oc} slightly increases from 640.3 mV to 640.7 mV as the wafer thickness decreases from 300 μm to 150 μm, then V_{oc} decreases to 640.125 mV as the wafer thickness further decreases to 50 μm. This phenomenon can be explained by considering the holes transport from front surface to back emitter, as shown in Fig. 2(c). The holes excited by the photons within the absorption depth can reach the back emitter by diffusion. In this process, the concentration of photon-generated holes is dependent on the photon flux density and the distance from

front surface x as given by

$$p(x,\lambda) = -\frac{\mathrm{d}\Psi(x,\lambda)}{\mathrm{d}(x)} = \alpha_\lambda \Psi_0(\lambda)\exp(-\alpha_\lambda x), \qquad (2)$$

where $\Psi_0(\lambda)$ is the photon flux density incident on the front surface and is the absorption coefficient. The concentration of holes which reach the back emitter for each wavelength by diffusion $p_\mathrm{d}(\lambda)$ can be calculated from the following equation:

$$p_\mathrm{d}(\lambda) = p(x,\lambda)\exp\left(-\frac{w-x}{l_\mathrm{p}}\right), \qquad (3)$$

where W is the wafer thickness and is the diffuse length of holes.

The total photon-generated holes reaching the back emitter can then be calculated by integrating the left-side of Eq. (3) with respect to all involved wavelength and the V_oc can be obtained by combining Eqs. (1), (2), and (3). Figure 2(b) shows the calculated results. Compared with the results obtained by the TCAD model, the V_oc exhibits a similar behavior as a function of wafer thickness and τ_bulk. Therefore, the model involving hole generation and diffusion can well explain the effect of wafer thickness on V_oc for different substrate lifetimes. The difference between these results achieved by the two methods arise as the horizontal transmission of holes and back reflection are ignored in the calculations.

Figure 3(a) shows the variations of J_sc of IBC solar cells with wafer thickness as τ_bulk decreases. For the substrate with 2 ms τ_bulk, the value of J_sc gradually decreases from 37.39 mA/cm^2 to 32.74 mA/cm^2 as the wafer thickness decreases from 300 μm to 50 μm. The same behavior is found for the substrate with 1 ms τ_bulk.

However, the values of J_sc exhibit different wafer thickness dependences as the τ_bulk further decreases. For example, for the substrate with 500-μs lifetime, the value of J_sc increases from 35.62 mA/cm^2 to 35.81 mA/cm^2 first with the wafer thickness decreasing from 300 μm to 250 μm and then decreases to 32.64 mA/cm^2 with the wafer thickness further decreasing to 50 μm. The same behavior is found for the solar cells using the substrate with lower τ_bulk. The maximum values of J_sc are observed to be 34.77 mA/cm^2, 33.6 mA/cm^2, and 32.49 mA/cm^2 for the τ_bulk values of 250 μs, 125 μs, and 62.5 μs when the wafer thickness values are 150 μm, 100 μm, and 100 μm, respectively.

To explain this phenomenon, the calculated values of external quantum efficiency (EQE) of IBC cells with various wafer thickness values for the τ_bulk of 2 ms and 62.5 μs are plotted in Figs. 3(b) and 3(c), respectively. It can be seen that the EQE begins to decrease quickly as the absorption depth becomes longer than wafer thickness at a specific wavelength. This wavelength is defined as critical wavelength λ_c hereafter, and the values of λ_c are variable corresponding to different wafer thickness values.

For the substrate with 2-ms τ_bulk, the EQE at the wavelength ranging from 500 nm to the λ_c changes a little with wafer thickness. Therefore, J_sc is mainly determined by the value of λ_c. A higher λ_c will increase the absorption of photons at the wavelength within the $\Delta\lambda_\mathrm{c}$, hence more carriers can be generated. Figure 3(b) shows that the λ_c shifts to the longer wavelength as the wafer thickness increases, which results in increasing J_sc for thicker wafer. The same principle can be applied to the substrate with 1-ms τ_bulk.

For the substrate with 62.5-μs τ_bulk, the wavelength λ_i is determined as the curves intersect where the EQE values of two IBC solar cells with different substrate thickness are equal. The figure indicates that the EQE decreases as the wafer thickness increases at the wavelength shorter than λ_i due to the recombination of electrons and holes. However, at the wavelength longer than λ_i, the EQE increases with wafer thickness decreasing as the result of the increase in absorption of long wavelength photons. Therefore, when wafer thickness increases, the change of J_sc is determined by compromising between the decreasing of the integrated value of EQE for wavelength lower than λ_i and the increasing of integrated value of EQE for wavelength higher than λ_i. To quantify the relationship of EQE with wafer thickness for 62.5-μs substrate, the integrated values of EQE are plotted in Fig. 3(d). The change of J_sc with wafer thickness is also shown in Fig. 3(d). The same changes tend to verify our point of view.

The fill-factor (FF) of IBC solar cells is also affected by both τ_bulk and wafer thickness. Our simulation results show that the shunt resistance decreases with τ_bulk decreasing, which results in the decreasing of FF for a given wafer thickness. For example, FF changes from 67.7% to 63.5% as lifetime decreases from 2 ms to 62.5 μs for 50-μm substrate. Moreover, for a given τ_bulk, the series resistance increases and the shunt resistance decreases with the wafer thickness scaling down, both leading to the decrease in FF.

Figure 4 shows the variations of final efficiency (EFF) with wafer thickness for various τ_bulk values of substrate. For the high τ_bulk (such as 2 ms) substrates, reducing substrate thickness causes the decrease in EFF. Diffusion coefficient in silicon substrate is 13 cm^2/s,[12] 2-ms τ_bulk makes diffusion length reach 1612 μm, which is much larger than the thickness of substrate. Therefore, bulk recombination is not the limiting factor in the performance of IBC solar cells, and the absorption of photons will decrease when a thinner substrate is used. For the low τ_bulk (such as 62.5 μs) substrates, diffusion length is 285 μm, which is smaller than the thickness of

300-μm substrate. Reducing substrate thickness will increase the number of minority carriers (holes) which can reach the rear surface of IBC solar cells; therefore, the EFF increases at first. When the thickness of substrate is below 100 μm, the influence of reducing photon-absorption on performance of IBC solar cells exceeds that of increasing holes; therefore, the EFF decreases when substrate continues to scale down. For the substrate with τ_{bulk} value between 2 ms and 62.5 μs, the maximum EFF can be obtained by optimizing wafer thickness for various τ_{bulk} values. For example, the optimized thickness values are 300 μm, 250 μm, 200 μm, and 150 μm for the τ_{bulk} values of 1 ms, 500 μs, 250 μs, and 125 μs, respectively.

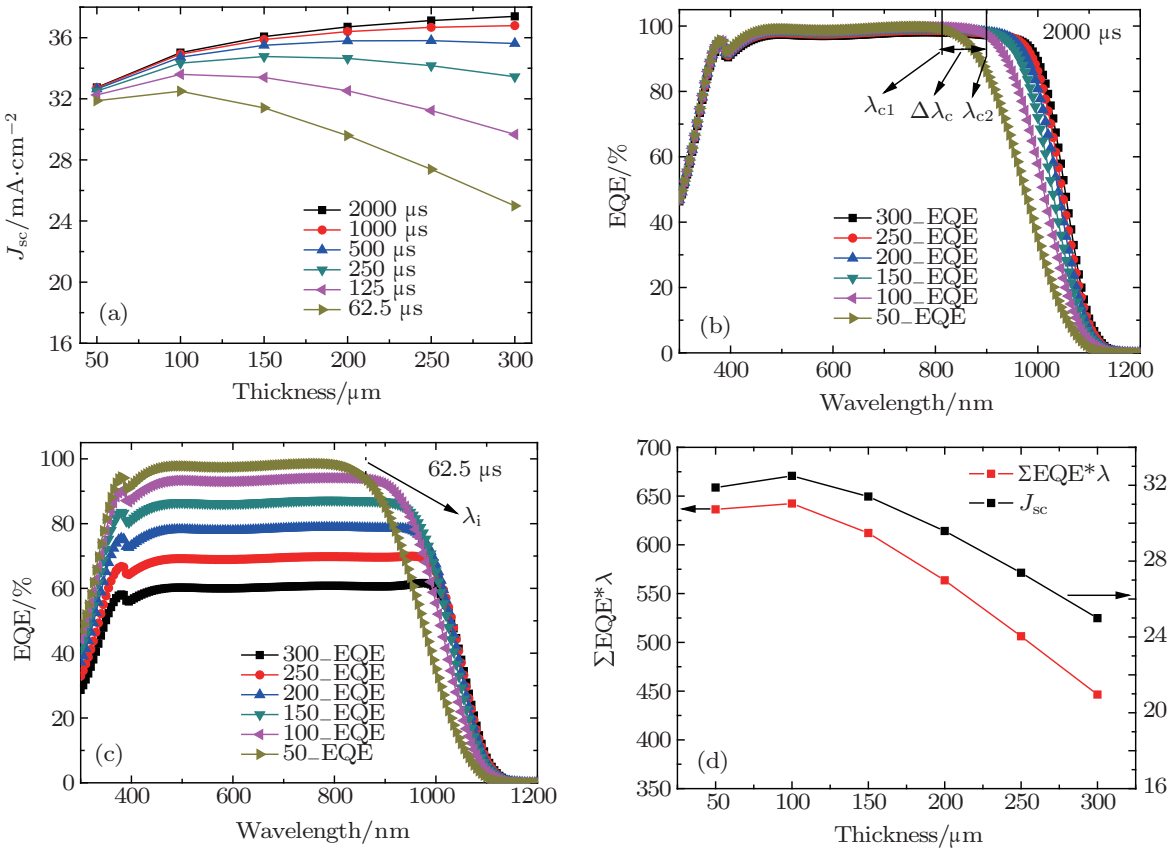


Fig. 3. (color online) (a) Variations of TCAD simulated short circuit current density with wafer thickness with τ_{bulk} decreasing, (b) variations of calculated EQE of IBC solar cells with substrate thickness for 2-ms τ_{bulk}, (c) variations of calculated EQE of IBC solar cells with substrate thickness for 62.5-μs τ_{bulk}, and (d) variations of integrated EQE with substrate thickness for 62.5-μs τ_{bulk}.

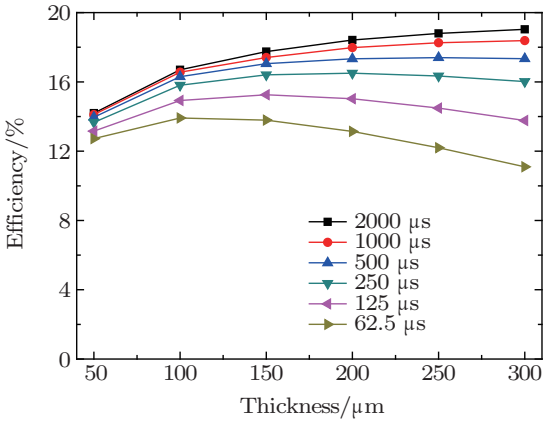


Fig. 4. (color online) Variations of calculated efficiency with wafer thickness for various substrate lifetimes.

During the simulation, in order to highlight the influence of bulk lifetime on the device properties, we assume that the whole IBC solar cell has a good front and back surface passivation with $S = 10$ cm/s. In this situation, τ_{eff} is determined by τ_{bulk}, which can be explain by the following equation[13]

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surf}} = \frac{1}{\tau_{bulk}} + \frac{2S}{W}, \tag{4}$$

where W is the thickness of the substrate. In fact, the above conclusions on τ_{bulk} should be changed into the ones on τ_{eff} in consideration of S. If $S = 100$ cm/s, for the high τ_{bulk} (such as 2 ms) substrate, τ_{eff} is determined by surface (S and W), EFF will decrease more quickly as W decreases because τ_{eff} also decreases. For the low τ_{bulk} (such 62.5 μs) substrate, τ_{eff} is determined first by τ_{bulk}, then by surface as W decreases. Therefore, bulk recombination will increase for low W and EFF may increase directly as W scales down.

4. Conclusions

In order to clearly illustrate the influence of τ_{bulk}decreasing and wafer thickness scaling down on the per-

formance of IBC solar cells, a 2D simulation tool TCAD is used to calculate the changes of V_{oc}, J_{sc}, FF, and EFF of IBC solar cells with τ_{bulk} values and wafer thickness. For a substrate with high τ_{bulk}, the V_{oc} first slightly increases then falls as wafer thickness decreases. However, for a substrate with low τ_{bulk}, the V_{oc} increases linearly as wafer thickness scales down. We use a physical model which combines the absorption of photons and diffusion of holes to explain this tendency. For a substrate with high τ_{bulk}, J_{sc} decreases as the wafer thickness decreases. For the substrate with low τ_{bulk}, the J_{sc} first increases and then falls as wafer thickness scales down. Different changes of EQE curves with various thickness values for different τ_{bulk} values are plotted to explain this phenomenon. Moreover, FF decreases as the values of both τ_{bulk} and wafer thickness reduce. The effects of V_{oc}, J_{sc}, and FF induce the EFF to change with substrate lifetime and wafer thickness. The influence of reducing τ_{bulk} on IBC solar cells becomes increasingly weaker as wafer thickness scales down due to the reduced absorption of light for long wavelengths. Therefore, an optimizing light trapping technology needs to be developed to prevent EFF from decreasing.

References

[1] ITRPV, "International Technology Roadmap for Photovoltaic (ITRPV) 2013 Results," 2013

[2] Cousins P, Smith D, Luan H C, Manning J, Dennis T, Waldhauer A, Wilson K, Harley G and Mulligan W 2010 35*th IEEE Photovoltaic Specialists Conference* (PVSC 2010), June 20–25, 2010, Honolulu, Hawaii, USA, p. 000275

[3] Aleman M, Das J, Janssens T, Pawlak B, Posthuma N, Robbelein J, Singh S, Baert K, Poortmans J and Fernandez J 2012 *Energy Procedia* **2** 7638

[4] Garner C, Nasby R and Sexton F 1980 *Electron. Dev. Lett.* **1** 256

[5] Granek F 2009 "High-efficiency back-contact back-junction silicon solar cells", Ph. D. Dissertation (Freiburg im Breisgau: Fraunhofer Institut für Solare Energiesysteme)

[6] Zhou C L, Wang W J, Li H L, Zhao L and Diao H W 2008 *Chin. Phys. Lett.* **25** 3005

[7] Silvaco 2000 *International* 2000 *A. U. Manual*, Vol. 95054

[8] Kim U C and Jiang X Q 2012 *Chin. Phys. Lett.* **29** 067301

[9] Schmidt J, Merkle A, Brendel R, Hoex B, Van de Sanden M and Kessels W 2008 *Progphotovoltaics* **16** 461

[10] Griffin P B, Plummer J D and Deal M D 2000 *Silicon VLSI technology: fundamentals, practice, and modeling* (Newyork: Prentice Hall Inc.) p. 102

[11] Bowden S, Yelundur V and Rohatgi A 2002 29*th IEEE Photovoltaic Specialists Conference* (PVSC 2002), May 19–24, 2002, Los Angeles, New Orleans, USA, p. 371

[12] Liu E K, Zhu B S and Luo J S 2011 *The Physics of Semiconductor* (Beijing: Publishing House of Electronics Industry) p. 56 (in Chinese)

[13] Gong C, Simoen E, Posthuma N, Van Kerschaver E, Poortmans J and Mertens R 2010 *Appl. Phys. Lett.* **96** 103507