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Research Article

High Improvement in Conversion Efficiency of μc-SiGe Thin-Film Solar Cells with Field-Enhancement Layers

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The improved performance for hydrogenated microcrystalline silicon-germanium (μc-$Si_{1-x}Ge_x$:H, $x \sim 0.1$) p-i-n single solar cells with hydrogenated microcrystalline silicon (μc-Si:H) field-enhancement layers (FELs) is demonstrated for the first time. The fill factor (FF) and conversion efficiency (η) increase by about 19% and 28% when the thickness of the μc-Si FEL is increased from 0 to 200 nm, it is attributed to the longer hole life-time and enhanced electric field in the μc-$Si_{0.9}Ge_{0.1}$:H layer. Therefore, we can successfully manufacture high-performance μc-SiGe:H solar cells with the thickness of absorbers smaller than 1 μm by conducting FELs. Moreover, the simulation tool is used to simulate the current-voltage (J-V) curve, thus we can investigate the carrier transport in the absorber of μc-$Si_{0.9}Ge_{0.1}$:H solar cells with different EFLs.

1. Introduction

In order to enhance the infrared absorption of thin-film solar cells, many efforts have been developed such as textured substrates or alloy absorbers. Textured substrates efficiently scatter incoming light and increase the optical length in absorbers [1]. However, rough morphology of the substrates can induce many cracks in absorption layers and damage the photocarrier transport [2]. The alternative methods, that is, high absorption coefficient alloy absorbers such as hydrogenated microcrystalline silicon-germanium (μc-$Si_{1-x}Ge_x$:H), have been developed for thin-film solar cells [3]. It has been reported that light absorption coefficient of μc-$Si_{1-x}Ge_x$:H films can be enhanced about from 4×10^2 to 4×10^3 cm^{-1} (@ 900 nm) when the Ge content is increased from 0 to 60 at. % [4, 5]. Moreover, Takuya Matsui et al. have demonstrated that a micromorph tandem cell with a μc-$Si_{1-x}Ge_x$:H ($x = 0.1$) bottom cell can reveal an initial conversion efficiency of 11.2% [6]. However, the incorporation of Ge may induce strain defects, dangling bond defects [7, 8], and acceptor-like states [4], hence it can result in reduced electric field in the absorbers.

Here, hydrogenated microcrystalline silicon (μc-Si:H) field-enhancement layers (FELs) are developed to improve the performance of μc-$Si_{1-x}Ge_x$:H p-i-n single solar cells for the first time, and we optimize the thickness of the FEL based on the conversion efficiency. Moreover, Atlas device simulator from SILVACO company is used to simulate the current-voltage curve of thin film solar cells. We analyze the band diagram and electric field in the device, the simulation results demonstrate that the FEL can enhance the hole life-time and electric field in the μc-$Si_{0.9}Ge_{0.1}$:H absorber.

2. Device Fabrication

In this study, superstrate-type μc-$Si_{1-x}Ge_x$:H single cells are fabricated on Asahi type-U glass substrates by a 40 MHz plasma enhanced chemical vapor deposition (PECVD) system. The single cell consists of Asahi type-U glass/ZnO:Ga(GZO)/p-μc-Si:H/μc-$Si_{1-x}Ge_x$:H buffer layer/i-μc-$Si_{0.9}Ge_{0.1}$:H/μc-Si:H FEL/n-μc-Si:H/GZO/Ag. The schematic diagram is shown in Figure 1. The buffer layer is graded intrinsic μc-$Si_{1-x}Ge_x$:H and its thickness is about 75 nm, it is obtained by varying hydrogen-diluted (10%) GeH_4 gas flow

Table 1: Material parameters.

Parameters	μc-$Si_{0.9}Ge_{0.1}$:H				μc-Si:H
	FEL = 0 nm	FEL = 100 nm	FEL = 200 nm	FEL = 300 nm	
Optical gap (eV)	1.24				1.3
Elec. mob. (cm^2/Vs)	20				30
Hole mob. (cm^2/Vs)	2				2
Con. Band DOS (cm^{-3})	1×10^{20}				1×10^{20}
Val. Band DOS (cm^{-3})	1×10^{20}				1×10^{20}
Hole life-time (s)	5.0×10^{-10}	1.2×10^{-9}	1.7×10^{-9}	8.0×10^{-10}	1×10^{-7}
Tail states density factor:					
Con. Band (cm^{-3}/eV)	5.0×10^{19}	5.2×10^{19}	5.3×10^{19}	5.6×10^{19}	1.0×10^{19}
Val. Band (cm^{-3}/eV)	5.0×10^{19}	5.2×10^{19}	5.2×10^{19}	5.3×10^{19}	1.0×10^{19}
Tail states charact. energy:					
Con. Band (eV)	0.027				0.027
Val. Band (eV)	0.045				0.045
Accepter-like Gaussian defect states:					
Below con. band (eV)	0.4				0.4
Decay energy (eV)	0.2				0.2
DOS (cm^{-3}/eV)	7.0×10^{16}	7.0×10^{16}	7.0×10^{16}	7.1×10^{16}	1.0×10^{15}
Donor-like Gaussian defect states:					
Above val. band (eV)	0.45				0.45
Decay energy (eV)	0.2				0.2
DOS (cm^{-3}/eV)	7.0×10^{16}				1.0×10^{15}

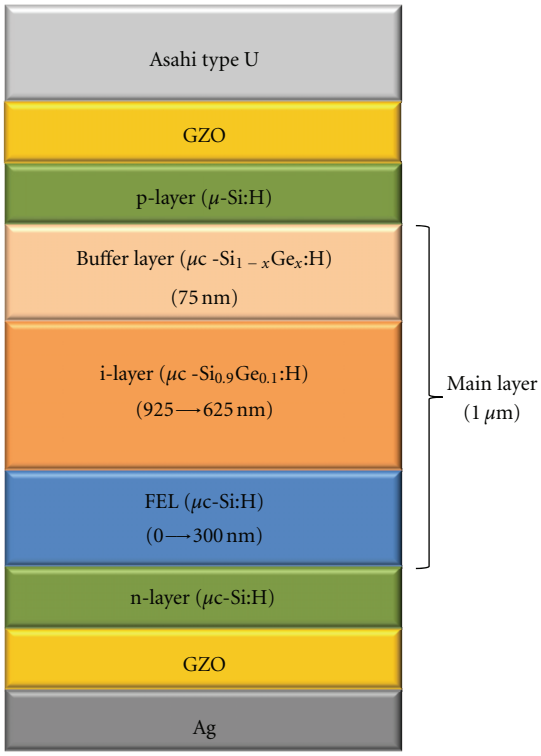


Figure 1: Schematic diagram of the μc-$Si_{0.9}Ge_{0.1}$:H p-i-n solar cell with the graded μc-$Si_{1-x}Ge_x$:H buffer layer and μc-Si:H FEL.

rate ([GeH_4]) from 0 to 4 sccm under a constant SiH_4 gas flow rate ([SiH_4]) of 17 sccm. The i-μc-$Si_{0.9}Ge_{0.1}$:H absorber is deposited at a fixed [GeH_4] of 5 sccm and an [SiH_4] of 17 sccm. The μc-Si:H FEL is grown at a constant [SiH_4] of 20 sccm and its thickness is varied from 0 to 300 nm. The main layer of solar cells consists of the buffer layer, the absorber, and the FEL and the total thickness is kept 1 μm.

The Raman spectra are performed by Confocal Raman Microscope (HOROBA, LabRAM HR) at room temperature in the backscattering configuration. The source light is Helium-Neon (HeNe) laser emitting at a wavelength of 632.8 nm. The Ge content of μc-$Si_{1-x}Ge_x$:H films can be identified from the Raman spectra. Edge isolation is conducted by the laser scriber to define the device area of 1.0 cm^2. The current-voltage (J-V) characteristics of solar cells are measured under an Air Mass 1.5 Global (AM 1.5 G) spectrum with an irradiation of 100 mW/cm^2 by a solar simulator.

We use Atlas to calculate internal electrical characteristics of solar cells in the one-dimension (perpendicular to the substrate). The simulation is based on J-V measurement results. Here, Newton method is used to solve Poisson's and continuity equations for the steady state. The carrier occupation and recombination in the forbidden gap states are considered by the Shockley-Read-Hall (SRH) recombination model. Table 1 shows the basic parameters in the μc-$Si_{0.9}Ge_{0.1}$:H and μc-Si:H layers.

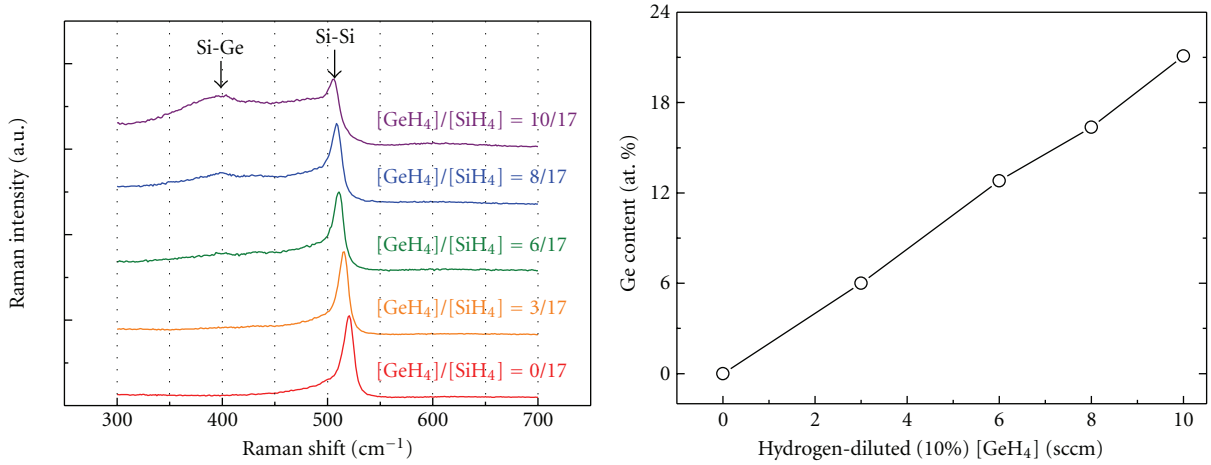
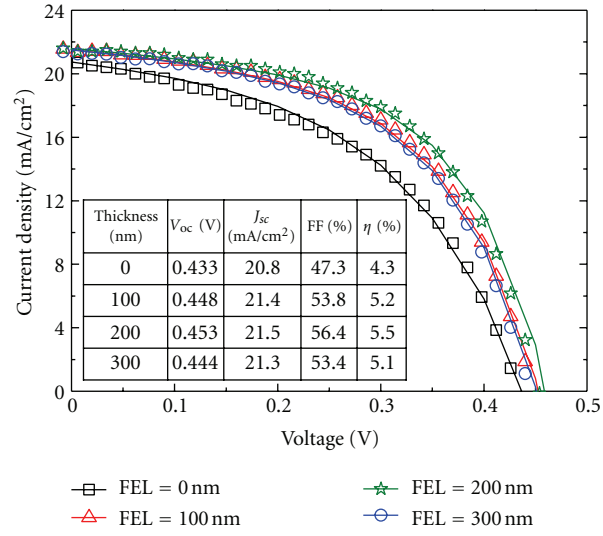


FIGURE 2: (a) Raman spectra of μc-$Si_{1-x}Ge_x$:H films deposited at different $[GeH_4]/[SiH_4]$ ratios. (b) The Ge content of μc-$Si_{1-x}Ge_x$:H films deposited at different $[GeH_4]$ estimated from Raman spectra.

3. Results and Discussion

Raman spectra of μc-$Si_{1-x}Ge_x$:H deposited at different gas flow rates ($[GeH_4]$: 0–10 sccm, $[SiH_4]$: 17 sccm) are presented in Figure 2(a). When the Ge content of μc-$Si_{1-x}Ge_x$:H films is increased, the main peak (ω_{Si-Si}) corresponding to the Si-Si transverse optical (TO) mode in the crystalline phase will gradually be lower than 520 cm^{-1} and the peak near 400 cm^{-1}attributed to Si-Ge bond will be apparent. The relation between the Ge content and ω_{Si-Si} is depicted as [6]: $\omega_{Si-Si} = 520–70\,x$. Figure 2(b) shows the nearly linear relation between the Ge content of μc-$Si_{1-x}Ge_x$:H films and the GeH_4 gas flow rate, hence we can estimate the Ge content of the absorber at about 10 at. %.

J-V measurement and simulation curves of μc-$Si_{0.9}Ge_{0.1}$:H solar cells with different μc-Si:H FELs are shown in Figure 3. The inserted table shows the *J-V* parameters of μc-$Si_{0.9}Ge_{0.1}$:H solar cells. When the thickness of the FEL is widened from 0 to 200 nm, the open-circuit voltage (V_{oc}) is increased from 0.433 to 0.453 V and the short-circuit current density (J_{sc}) is enhanced from 20.8 to 21.5 mA/cm^2. In addition, the fill factor (FF) is enhanced from 47.3 to 56.4% and conversion efficiency (η) is enhanced from 4.3 to 5.5%. Quantum efficiency (QE) spectra of μc-$Si_{0.9}Ge_{0.1}$:H solar cells (FEL = 0, 200 nm) at a reverse bias of 0 and −0.5 V are shown in Figure 4. Under a reverse bias of 0 and −0.5 V, QE spectra of the μc-$Si_{0.9}Ge_{0.1}$:H solar cell without FEL are divided apparently. However, the μc-$Si_{0.9}Ge_{0.1}$:H solar cell with the 200 nm FEL exhibits more matching QE spectra in the wavelength range of 500–800 nm. This result implies that the μc-$Si_{0.9}Ge_{0.1}$:H solar cell equipping with the FEL has the enhanced electric field in the μc-$Si_{0.9}Ge_{0.1}$:H layer. However, the FF and η decrease to 53.4% and 5.1% when the FEL rises to 300 nm, but V_{oc} and J_{sc} do not suffer severely. Consequently, we found that 200 nm is the optimized thickness of the FEL for solar cell.



Thickness (nm)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
0	0.433	20.8	47.3	4.3
100	0.448	21.4	53.8	5.2
200	0.453	21.5	56.4	5.5
300	0.444	21.3	53.4	5.1

FIGURE 3: *J-V* measurements of μc-$Si_{0.9}Ge_{0.1}$:H solar cells with μc-Si:H FEL varied from 0 to 300 nm.

Figure 5 (a) shows the band diagram in the main layer of the solar cell in thermodynamic equilibrium. Because the optical band gap of μc-Si:H is higher than one of μc-$Si_{0.9}Ge_{0.1}$:H, there must be a valance-band discontinuity in the p-i interface and the hole extraction might be block. Graded μc-$Si_{1-x}Ge_x$:H buffer layers are conducted to reduce this energy discontinuity and enhance the hole transport. Around the interface between the μc-$Si_{0.9}Ge_{0.1}$:H and the μc-Si:H FEL, the energy barrier seen by hole carriers can repel it and reduce recombination probability near the back side of the main layer. The simulation results based on the Shockley-Read-Hall (SRH) recombination model show that hole life-time can be enhanced from 5×10^{-10} to 1.7×10^{-9} s when the FEL is increased from 0 to 200 nm. Figure 5(b)

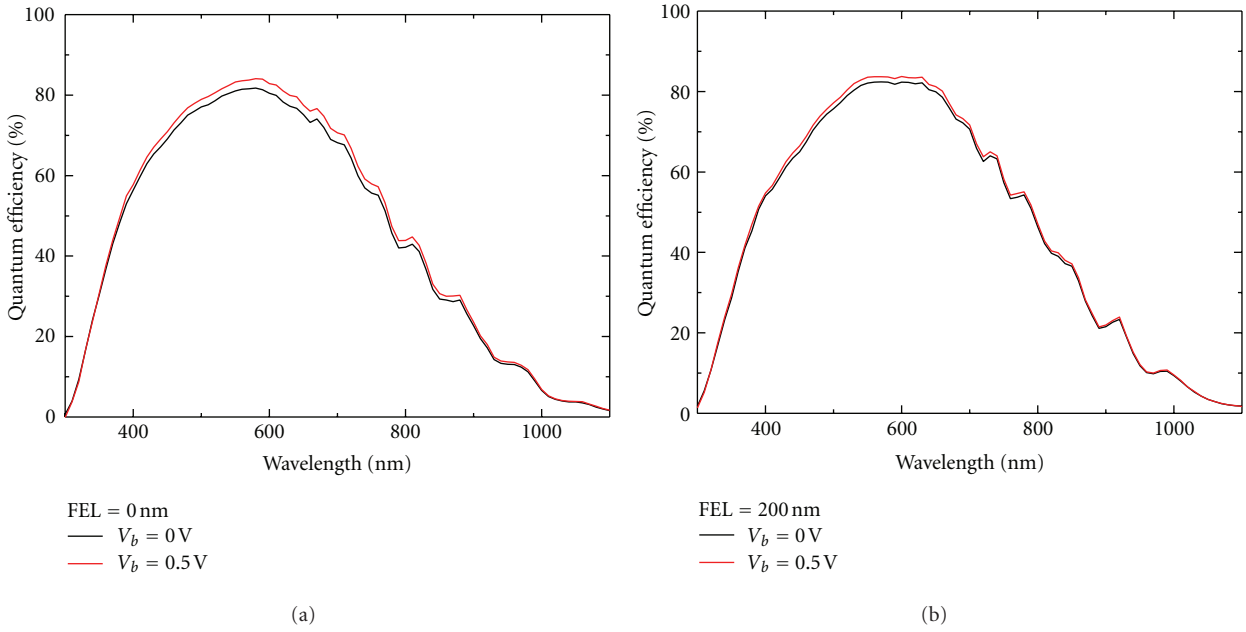


FIGURE 4: (a) QE spectra of the μc-$Si_{0.9}Ge_{0.1}$:H solar cell without FEL and (b) with FEL of 200 nm at a reverse bias of 0 and −0.5 V.

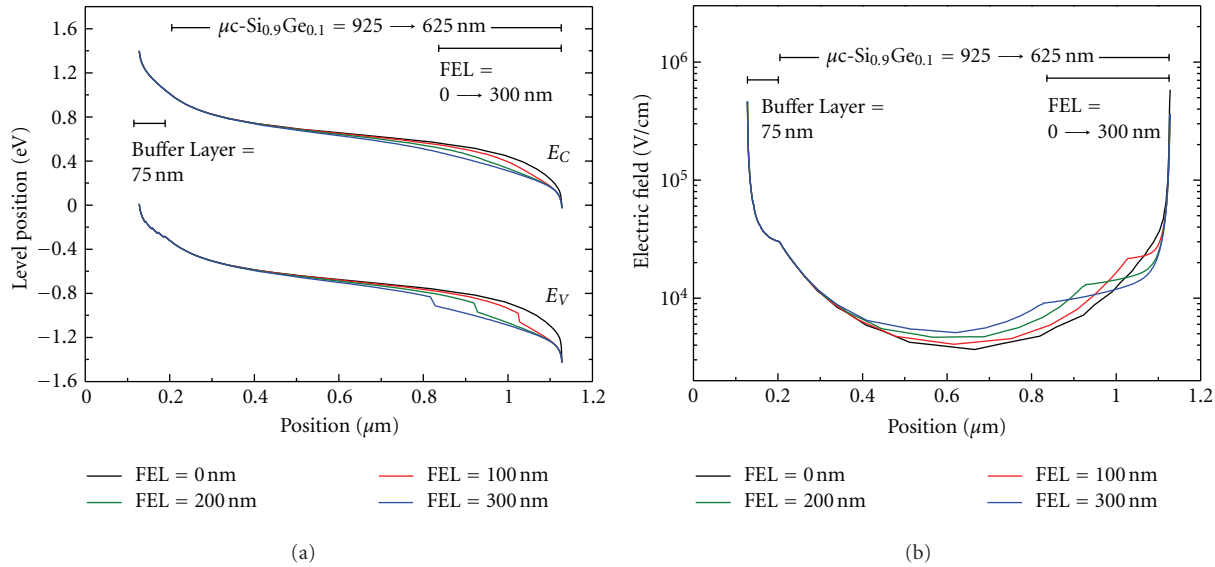


FIGURE 5: (a) The band diagram and (b) the electric field in the main layer of the solar cell with different μc-Si:H FEL in thermodynamic equilibrium.

shows the electric field of the main layer in thermodynamic equilibrium. When the thickness of the FEL is increased from 0 to 200 nm, the electric field in the μc-$Si_{0.9}Ge_{0.1}$:H layer can be enhanced significantly. This is because that μc-Si:H has lower defect density than μc-$Si_{0.9}Ge_{0.1}$:H and the field-screening effect related to trapped charges can be reduced efficiently. The enhanced electric field in the μc-$Si_{0.9}Ge_{0.1}$:H layer is useful for photocarrier extraction. The electric field in the μc-$Si_{0.9}Ge_{0.1}$:H layer can be increased further when we widen the FEL from 200 to 300 nm. However, the electric field in the thick FEL is decreased significantly. Additionally, we observe that hole life-time is reduced to 8×10^{-10} s when the FEL is 300 nm. This result is probably due to the poor crystallinity in a thinner μc-$Si_{0.9}Ge_{0.1}$:H layer. Hence, we speculate that diminished hole life-time and reduced electric field in the thick FEL result in the degraded performance of the solar cell.

4. Conclusion

High-performance μc-$Si_{0.9}Ge_{0.1}$:H single cells with the absorber smaller than 1 μm are achieved by equipping with μc-Si:H FELs. We use μc-Si:H FELs and graded μc-$Si_{1-x}Ge_x$:H buffer layers to improve the photocarrier

transport in the μc-$Si_{0.9}Ge_{0.1}$:H layers. The Ge composition of μc-$Si_{1-x}Ge_x$:H films can be evaluated quantitatively from Raman spectra. When we widen the thickness of the FEL from 0 to 200 nm, V_{oc} is enhanced from 0.433 to 0.453 V and J_{sc} is enhanced from 20.8 to 21.5 mA/cm^2. Moreover, FF and η approximately exhibit 19% and 28% enhancements. It is attributed to the improved electric field and longer hole lifetime in the μc-$Si_{1-x}Ge_x$:H layer. However, FF and η are both decreased when the thickness of the FEL exceeds 200 nm. This is due to poor crystalline μc-$Si_{0.9}Ge_{0.1}$:H layer and the reduced electric field in the thick FEL. There is a trade-off between the enhanced electric field in the absorber and the reduced one in the FEL.

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