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A Novel Surface Nano-Structure Design for SiGe/Si Type-II Hetero-Junction Solar Cell

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1. Introduction

As we known, Solar Cell is a very important product for the near future green technology industry and has a principal application. However, the bottleneck of the development for the cell is still located at the high cost for the mass production. In order to continuously reduce the cost for the mass production, higher efficient Solar Cell is needed to be developed and investigated urgently. There are many different methods and ways have been reported and developed by other groups recently to enhance the total power conversion rate and its corresponding final solar cell efficiency, including multi-junction III-V solar cell [1] and novel Si nano-hemisphere array surface texturing scheme [2]. Our group also demonstrated that the total reflection rate on Si-based solar cell with nano-level top surface trench structure [3] can be successfully reduced from 37% to 16% and then its corresponding cell efficiency can be also improved about ~3%. On the other hand, we also had investigated the advantages and benefits of SiGe-based solar cell than Si-based solar cell [4]. In this work, we combine these two key technologies together and demonstrate the high solar cell efficiency about 21%.

2. General Instructions

Fig. 1 shows our basic design concept in this work. Our previous work showed that the nano-level trench structure on the top surface of the solar cell can effectively reduce the visible reflection rate, and further enhance the visible light absorption and the final cell efficiency [3]. Furthermore, with the cooperation of Ge in Si substrate, SiGe/Si type-II hetero-structure cell also can result in higher visible absorption rate [4] and higher localized carrier concentration near the interface of Si/SiGe [5]. More electrons are accumulated at the conduction band of Si/SiGe hetero-junction, while more hole carriers are localized at SiGe quantum well (QW) structure [5]. Higher localized carrier concentration and longer non-radiative Auger recombination lifetime with the carrier separation in k-space (will explain it later in Fig. 3 in this work) in the designed SiGe/Si type-II hetero-junction structure lead to higher cell electric-optical transmission efficiency. With the successful combination of these two advanced technologies developed by our group previously [3-5], ~21% high efficient transmission can be achieved by our advanced nano-surface textured SiGe/Si type-II hetero-structure solar cell. The accurate Ge concentration and stress level in $Si_{1-x}Ge_x$ layer can be extracted by XRD and Raman spectra [6]. SiGe material with different Ge concentration and stress level has its corresponding energy band gap (Eg), energy band shift of the conduction band (ΔE_C) to the Si, and it of the valence band (ΔE_V) to the Si. These values could be extracted by the photoluminescence (PL) spectra with Electra-Hole-Plasma (EHP) recombination modeling [7] and the barrier height extraction in the strained Schottky Barrier device [8]. These experimental data are consistent with the theoretical calculation by Dr. Walle in Ref. 9.

Fig. 2 shows the reflection spectra (the range of wavelength for the visible light is between 400 nm to 700 nm) with different surface trench spacing (d) structure design. It can be found that the minimum in the reflectance spectra shifted as a function of the surface trench spacing (d), consistent with the finite differential time domain (FDTD) calculation. Indeed, FDTD simulation and theory revealed that the surface structure with smaller trench spacing (d) mainly absorbs short wavelength light. It also indicates that the surface structure having different trench spacing may realize broadband antireflection among the visible region. Our experimental data show that the designed irregular surface trench spacing can contribute lower surface reflectance among the visible light region about 3 times (totally from 32% to ~10%) and further leads to higher solar cell efficiency about 3% in this work.

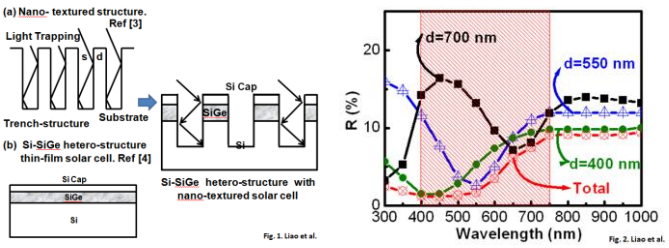


Fig. 1 The basic concept and device structure developed in this work.

Fig. 2 The reflection spectra with different designed surface trench spacing (d) structures.

Besides the design of the top cell surface structure shown in Fig. 2, the energy band optimization for the cell substrate is also very important for the efficiency improvement. With the cooperation of Ge in Si substrate, the Eg, ΔE_C, and ΔE_V of the type-II SiGe/Si hetero-junction cell could be modified and optimized, due to the different Ge concentration effect in SiGe [9] and stress effect [9-10]. The accurate definition of Eg, ΔEc, and ΔEv in SiGe/Si hetero-structure in this work are labeled in Fig. 3(b) for the reference. Fig. 3(a) shows the PL spectra with higher laser power excitation on two $Si_{1-x}Ge_x$ samples, including Sample A: Fully strained-$Si_{0.9}Ge_{0.1}$/Si and Sample B: relaxed-$Si_{0.8}Ge_{0.2}$/Si. The obvious blue-shift (>15 mV) can be found in the PL spectra under the high laser excitation in Sample A: Fully strained-$Si_{0.9}Ge_{0.1}$/Si, while there is no any

blue-shift in Sample B: relaxed-$Si_{0.8}Ge_{0.2}$/Si. The experimental result (blue energy shift) indicates that Sample A: Fully strained-$Si_{0.9}Ge_{0.1}$/Si band structure is type-II-like band alignment, which agrees well with the theoretical calculation [9], because more electron carriers are confined and accumulated at the Si cap conduction band region and have the quantum effect in Si/SiGe type-II band structure. Type-II band alignment has two advantages for the solar cell efficiency improvement. The first one is higher accumulated and localized carrier concentration, which will be explained and simulated in Fig. 4, due to the quantum effect. Another one is longer Auger non-radiative recombination rate in type-II SiGe/Si hetero-junction. Fig. 3 (b) shows the carton of the energy-band structure with different types of hetero-structure device under high laser excitation for the reference.

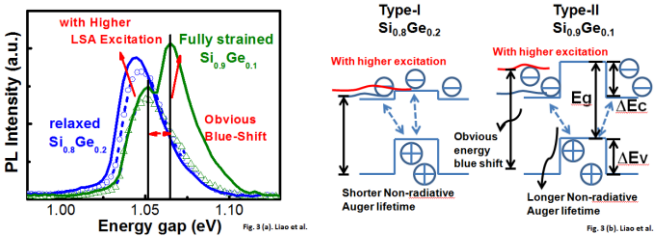
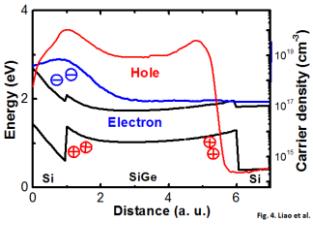


Fig. 3 (a) PL spectra with different excitation power on different SiGe concentration samples. (b) The carton of the energy-band structure with different Ge concentration under high laser excitation.

Fig. 4. simulates the electron and hole carrier distribution in Sample A: Fully strained-$Si_{0.9}Ge_{0.1}$/Si type-II band structure device. The energy band offset between Si and fully strained-$Si_{0.9}Ge_{0.1}$ layer results in the SiGe QW structure and type-II hetero-junction. Electrons can be accumulated at the Si/SiGe interface on the conduction band and hole can be accumulated at the SiGe QW layer on the valence band. This type-II band structure can result in higher carrier concentration due to the quantum confinement. Another benefit in this type-II hetero-junction structure is with longer Auger non-radiative recombination lifetime, due to the different k-space positions and separation for the electron and hole in the energy band diagram shown in Fig. 4 and Fig. 3(b). With the real femto-second transient absorption and temporal response of electroluminescence measurement (Detail can refer to our previous work in Ref. 11.) for Si and Sample A: Fully strained-$Si_{0.9}Ge_{0.1}$/Si, the Auger non-radiative lifetime in Si and Sample A: Fully strained-$Si_{0.9}Ge_{0.1}$/Si show ~0.5 nS and ~23 nS, respectively. The strained $Si_{0.9}Ge_{0.1}$/Si type-II hetero-junction device indeed has longer (about 40 times) non-radiative recombination rate than our control Si device. Both higher localized carrier concentration and longer Auger non-radiative recombination rate [11] in SiGe/Si type-II hetero-structure can benefit higher solar cell efficiency improvement about ~3% in Fig. 5.

3. Conclusions

With the successful integration of nano-surface trench structure design having lower visible light reflection rate (Fig. 2) and SiGe/Si type-II band alignment, leading longer non-radiative (Auger) recombination time and higher accumulated carrier (Fig. 3(b) and Fig. 4), ~21% high efficient solar cell can be achieved. Totally 6% efficiency improvement (~3% for each individual knob) can be demonstrated under the combination of these two advanced technologies. We prove that ~21% high efficiency of nano-surface trench structure SiGe/Si type-II solar cell has high competitiveness for the future real industry application.



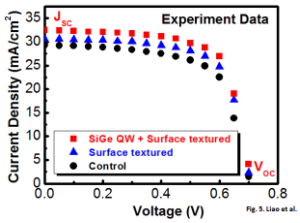


Fig. 4 The type-II band structure and carrier concentration in $Si_{0.9}Ge_{0.1}$ sample, simulated by ISE tool.

Fig. 5 High efficient ~21% solar cell efficiency by nano-surface trench structure.

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