

Research Article

Characterization of Nanocrystalline SiGe Thin Film Solar Cell with Double Graded-Dead Absorption Layer

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The nanocrystalline silicon-germanium (nc-SiGe) thin films were deposited by high-frequency (27.12 MHz) plasma-enhanced chemical vapor deposition (HF-PECVD). The films were used in a silicon-based thin film solar cell with graded-dead absorption layer. The characterization of the nc-SiGe films are analyzed by scanning electron microscopy, UV-visible spectroscopy, and Fourier transform infrared absorption spectroscopy. The band gap of SiGe alloy can be adjusted between 0.8 and 1.7 eV by varying the gas ratio. For thin film solar cell application, using double graded-dead i-SiGe layers mainly leads to an increase in short-circuit current and therefore cell conversion efficiency. An initial conversion efficiency of 5.06% and the stabilized efficiency of 4.63% for an nc-SiGe solar cell were achieved.

1. Introduction

The band gap of amorphous silicon-germanium (a-SiGe) alloy can be adjusted between 1.4 and 1.7 eV by varying the Ge fraction. This characteristic renders a-SiGe a suitable light absorber material in multijunction amorphous-silicon- (a-Si-) based thin film solar cells, in which the a-SiGe acts as intrinsic layer in middle cells to enhance green-to-red absorption [1, 2]. Though the electronic properties deteriorate with Ge alloying, some earlier studies have shown that these properties can be improved when alloys are deposited at high pressure and high hydrogen dilution [3, 4]. In recent years, significant improvements in solar cell performance were achieved by a band gap graded intrinsic i-layer [5]. However, the solar cells with those a-SiGe films show a significant light degradation [6].

In this work, nanocrystalline SiGe (nc-SiGe) films have been introduced to the single junction p-i-n solar cell, because of the enhanced response in longer wavelength (>650 nm) of solar spectrum and higher light-induced stability. The main structural and optical properties of nc-SiGe

samples deposited at different gas ratios were first described. Then, the double graded nc-SiGe films are used as absorption layer of a solar cell and its photovoltaic performance is also discussed.

2. Experimental

The SiGe films were deposited on glass using high-frequency (27.12 MHz) plasma-enhanced chemical vapor deposition (HF-PECVD) in an ultrahigh-vacuum, single-camber, load-locked deposition system. Table 1 listed the deposition conditions of SiGe films. The gas ratio x , which was defined as $[\text{GeH}_4]/([\text{SiH}_4] + [\text{GeH}_4])$, was changed from 0% to 100% to prepare SiGe films. The thickness for all samples was 700 nm. The samples were characterized by the scanning electron microscopy (SEM) to observe the surface morphology of the films. The spectra of optical absorption were measured by UV-visible spectroscopy for determination of the Tauc optical band gap (E_g) through [7]

$$(\alpha h\nu)^{1/2} = B(h\nu - E_g), \quad (1)$$

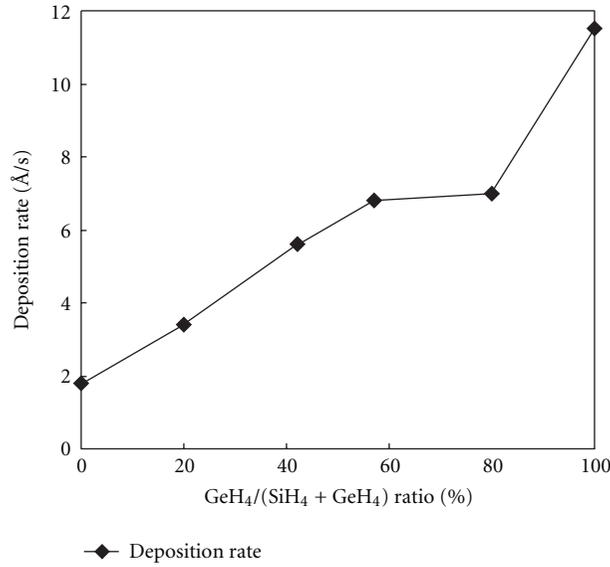


FIGURE 1: Variation of deposition rate as a function of the gas ratio.

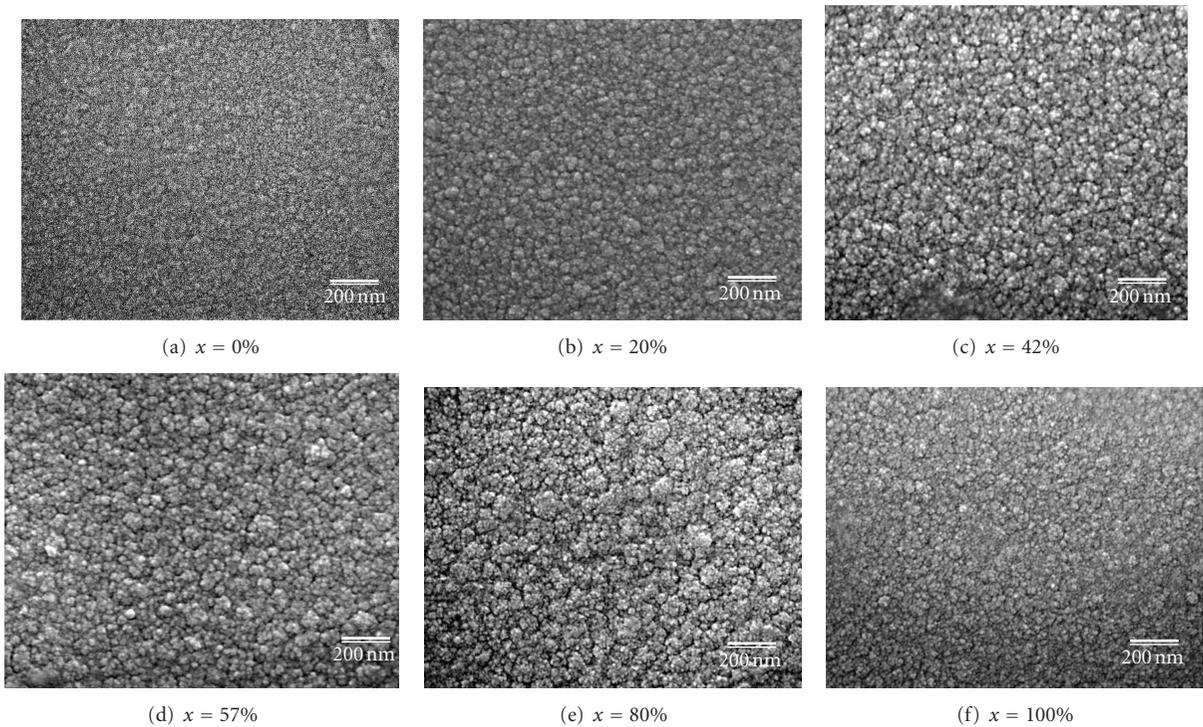


FIGURE 2: The SEM images of the SiGe films deposited at different gas ratios of (a) 0%, (b) 20%, (c) 42%, (d) 57%, (e) 80%, and (f) 100%.

where α , $h\nu$ and B are optical absorption coefficient, photon energy and Tauc slope, respectively. In addition, it is known that the absorption coefficient near the band edge shows an exponential dependence on photon energy [8]:

$$\alpha(\lambda) = \alpha_0 \exp\left(\frac{h\nu}{E_0}\right), \quad (2)$$

where E_0 is the Urbach energy which corresponds to the width of the band tail and can be evaluated as the width of the localized states and α_0 is a constant. Thus, an Urbach plot

of $\ln[\alpha(\lambda)]$ versus photon energy should be linear and optical absorption edge can be obtained from the slope.

Fourier transform infrared (FTIR) absorption measurements were taken for samples on c-Si substrates to obtain information of the concentrations of Ge-H and Si-H bonds. For solar cell application, single-junction p-i-n solar cells using these SiGe films as absorption layer were deposited on ASAHI (type-U) glass substrates. The current-voltage characteristics of the solar cell were measured at 100 mW/cm² by using an AM 1.5 G solar simulator. Light

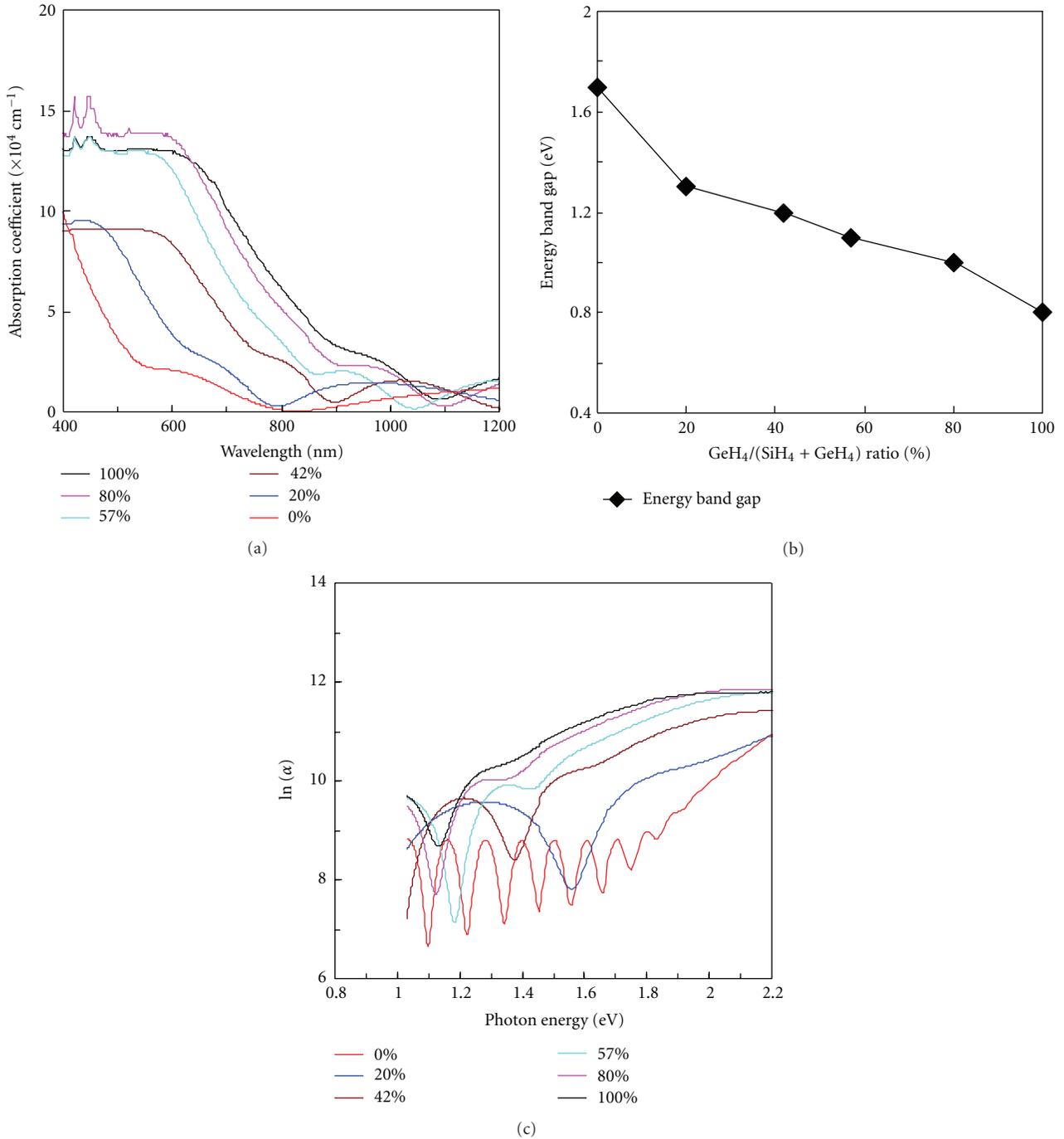


FIGURE 3: (a) The spectral dependence of the absorption coefficient for the SiGe films with different gas ratios. (b) The Tauc energy band gap as a function of the gas ratio. (c) The Urbach plots of the SiGe films with different gas ratios.

soaking was performed under one-sun light intensity using a metal halide lamp at 50°C for 500 h. The intensity was maintained at a level so that a reference Si solar cell generated the same current under a Xe-lamp simulator.

3. Results and Discussion

Figure 1 shows the variation in deposition rate as a function of gas ratio (x). It can be seen that the deposition rate ra-

pidly increases from 1.8 to 11.5 Å/sec with increasing x value from 0% to 100%. A reasonable explanation for this effect is that the addition of the GeH₄ flow rate favors the SiH₄ as well as GeH₄ dissociation, resulting in an increase of concentration of the precursors in the plasma during the deposition process, which causes a higher Si-Ge bond formation and therefore enhances the deposition rate [9]. The similar result was reported by other research groups [10, 11].

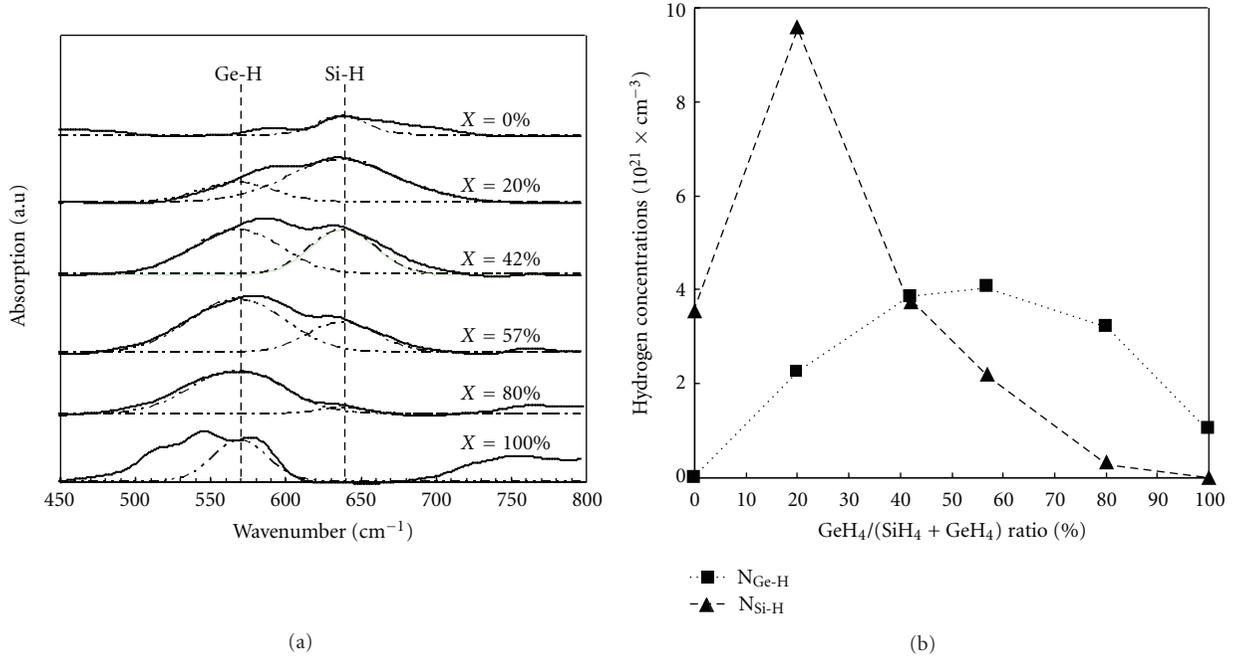


FIGURE 4: (a) Infrared coefficient absorption spectrums of the wagging mode of the a-SiGe:H films deposited at different germanium concentrations. (b) Variation of bonded hydrogen concentration in different configurations as function of the gas ratio.

TABLE 1: The deposition conditions of SiGe films.

Parameter	Value
Power (W)	15
Pressure (Pa)	40
Electrode distance (mm)	14
Substrate temperature (°C)	200
SiH ₄ flow rate (sccm)	40; 40; 40; 30; 10; 0
GeH ₄ flow rate (sccm)	0; 10; 30; 40; 40; 40
Gas ratio (%)	0–100

Figure 2 shows the surface morphologies of the SiGe films deposited at different x values of (a) 0%, (b) 20%, (c) 42%, (d) 57%, (e) 80%, and (f) 100% as observed by SEM. These images indicate that the germane-doped films have similar surface structure with grains in nanoscale (<100 nm). Thus, an increase of amount of germane incorporation to the alloys might promote the formation of nanocrystals.

Figure 3(a) shows the spectral dependence of the absorption coefficient for the SiGe films with different x values. It can be seen that the absorption coefficient obviously increases from about 9×10^4 to 13×10^4 cm⁻¹ when the x value increases to above 80%. In addition, the absorption edge of the SiGe film is shifted to long wavelength mainly due to a decrease in Tauc energy band gap, which is shown as a function of x values in Figure 3(b). The reduction in band gap can be relative to the crystalline phase in the films supported by the SEM results. The Urbach plots for different alloys are shown in Figure 3(c). It can be seen that the optical absorption edge shifts to lower energies when the x value increases. This result shows the similar trend to the Tauc band gap result.

The infrared absorption spectra of SiGe films with different x values are shown in Figure 4(a). The absorption bands of SiGe are assigned to the Si–H and Ge–H wagging vibration located at around 570 and 640 cm⁻¹, respectively [12]. The effect of germane on the alloys is seen in the shift of the peak from 640 cm⁻¹ for $x = 0\%$ to 570 cm⁻¹ for $x = 100\%$. For further investigation, the hydrogen bond concentrations $N(\text{Ge–H})$ and $N(\text{Si–H})$ of these SiGe films are determined by the following equation [13]:

$$N = A \int \frac{\alpha}{\omega} d\omega, \quad (3)$$

where α is the absorption coefficient and ω is the frequency. For the constant A , we use the value given in [12, 14]. The calculated results are shown in Figure 4(b), clearly showing that the Si–H bonds dominate the structure as the x value is below 20%. But when the x value increases above 20%, there is a preferential attachment of H atoms to Ge rather than Si.

Figure 5 shows a comparison of I - V characteristics between the solar cell constructed with single i-SiGe layer ($x = 42\%$, 1 μm thick) and the solar cell with double graded i-SiGe layer of i_1 ($x = 20\%$, 300 nm)/ i_2 ($x = 42\%$, 1 μm). These two cells have the same p-, n-layer, and back electrode (Ag) thickness of 20, 30, and 300 nm, respectively. The V_{oc} values are around 0.58 V showing no significant change, whereas the J_{sc} is higher in double graded-dead i-layer cell than that in single i-layer cell, implying that the carrier collection probability and/or carrier mobility are improved by the reduction of band gap discontinuity. Furthermore, the I - V curve after light soaking of our graded double i-layer is also plotted for the purpose of comparison, and the detailed external parameters are listed in Table 2. The cell conversion efficiency (η) decreases from 5.06% for initial to 4.63% for

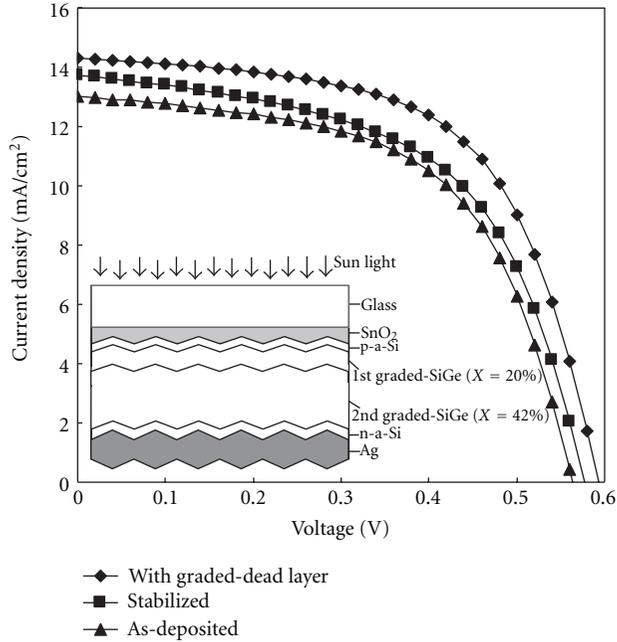


FIGURE 5: Schematic structure of the p-i-n solar cell with double graded-dead nc-SiGe i-layers and I - V characteristics of the solar cells without (as-deposited), with double graded-dead absorption layer, and after light-soaking test for 500 h.

TABLE 2: The external parameters of nc-SiGe thin film solar cells without (as-deposited), with double graded-dead i-layers, and after light-soaking test.

	V_{oc} (V)	J_{sc} (mA/cm ²)	FF (%)	η (%)
As-deposited	0.56	13.01	57.50	4.21
With graded-dead layer	0.59	14.30	59.70	5.06
Stabilized	0.58	13.74	58.12	4.63

stabilized (8.4% degradation), showing that the cell is stable against light soaking. From this result, we speculate that our SiGe solar cell with a reduced sensitivity to the optical degradation (the Staebler-Wronski effect [15, 16]) is mainly due to the crystalline structure of the i-layer.

4. Conclusions

The effects of GeH_4 gas ratio on growth mechanisms and properties of SiGe films are investigated in this paper. By controlling the gas ratio, nc-SiGe films with certain optical band gap can be obtained to be used as absorption layer for solar cell applications. Using double graded-dead i-SiGe layers can increase the J_{sc} and therefore cell conversion efficiency. Furthermore, an initial conversion efficiency of 5.06% and the stabilized efficiency of 4.63% for an nc-SiGe solar cell were achieved.

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