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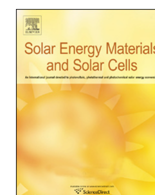

Short circuit current and efficiency improvement of SiGe solar cell in a GaAsP-SiGe dual junction solar cell on a Si substrate

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ABSTRACT

SiGe materials on Si substrate are promising candidates to act as the bottom cell in a tandem structure, due to its high mobility, good process compatibility, adjustable lattice constant, and capability of absorbing light of wavelengths up to 1800 nm. This work demonstrates the improvement of short circuit current and efficiency for the SiGe solar cell, operating in a GaAsP-SiGe two-terminal configuration tandem device. A numerical model is proposed to predict the short circuit current of the SiGe cell. Experimentally, the highest short circuit current density is increased from 12.9 mA/cm^2 to 19.4 mA/cm^2, with optimized fabrication process and device structure. The efficiency of the SiGe bottom cell is improved from 1.7% to 3.0% filtered by GaAsP. It is demonstrated that the cell has potential to achieve an efficiency of 4.6% at 20 suns illumination. Different mole fractions of Ge in the structure are confirmed from the X-ray diffraction line scanning image.

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1. Introduction

In photovoltaics, III–V multijunction solar cells have produced the highest efficiencies [1]. However, the use of high cost conventional substrates in the III–V multijunction devices limits their applications. The aim of this research is to fabricate a dual junction cell, grown on silicon substrate, which is able to achieve a 34% relative increase in theoretical efficiency over a single junction silicon solar cell [2–4].

The most important factors in choosing the material of the bottom cell in a two-terminal configuration are to minimize the lattice mismatch, and to ensure the current matching [2]. Silicon germanium (SiGe) is chosen to be applied as the bottom cell in our dual junction cell system, due to its high mobility, good process compatibility, adjustable lattice constant, and capability of absorbing light of wavelengths up to 1800 nm [5–7].

An efficiency of 18.9% under one sun has been reported from the gallium arsenide phosphide-silicon germanium (GaAsP-SiGe) structure [2]. More recently, Wang et al. [8,9] reported an efficiency of over 20% from the GaAsP-SiGe cell, with a threading dislocation density (TDD) in the III–V epitaxial layers as low as 2×10^5 cm^{-2}. To improve the dual junction cell performance further, a key factor is to improve the short circuit current density (J_{sc}) of the SiGe cell to 21.0 mA/cm^2, when it operates beneath the GaAsP top cell.

Previous work on SiGe solar cells grown on Si were mostly focused on SiGe solar cells with low Ge concentrations. Lower Ge concentration cell produces higher open circuit voltage (V_{oc}) with wider bandgap (E_g), which makes it unable to absorb photons with lower energy. Such cells cannot generate enough current when acting as the bottom cell in the GaAsP-SiGe device. In 1997, Gutjahr et al. [10] reported an efficiency of 9.1% for a $Si_{.9}Ge_{.1}$ solar cell. The $Si_{(1-x)}Ge_{(x)}$ layers were grown on Si substrate by liquid phase epitaxy (LPE) technology. In 1999, an 11.30% efficient SiGe solar cell was successfully fabricated by Said et al. [11]. The cell was grown with 10% concentration of Ge on Si using chemical vapor deposition (CVD) technology. However, these cells, when working under the GaAsP top cell, were calculated to produce a J_{sc} lower than 7.5 mA/cm^2. More recently, Wang et al. [12] reported fabricating a .79% efficiency SiGe cell under a Si filter below 30 suns, and this cell below a GaAsP top cell was calculated to have a J_{sc} of 10.1 mA/cm^2.

With a Ge concentration of 82%, a J_{sc} of 10.9 mA/cm^2 has been reported, from the SiGe bottom cell, in our previous paper [13]. In this work, a comprehensive analysis on the improvement of J_{sc} for SiGe single junction cells is provided. The achievable external

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quantum efficiency (EQE) is predicted. Experimental results demonstrate that the optimized fabrication process results in a J_{sc} as high as 17.2 mA/cm^2 for a $Si_{.18}Ge_{.82}$ cell, and 19.4 mA/cm^2 for a $Si_{.12}Ge_{.88}$ cell operating beneath the GaAsP device under AM1.5G spectrum. The efficiency of the SiGe cell itself is also improved from 1.7% to 3.0% at 1 sun illumination. At 20 suns illumination, an achievable efficiency of 4.6% is predicted according to the J_{sc}-V_{oc} measurement.

2. Numerical modeling and prediction

Achieving current matching is a crucial element of tandem cell design. Therefore the desired parameters of the SiGe bottom cell were first determined based on current-matching constraints. This was initiated from calculating the cumulative current, to determine the matched current of the GaAsP-SiGe tandem cell. The photon flux distribution under AM1.5G spectrum and AM1.5D spectrum are plotted in Fig. 1. The cumulative currents are shown by the dashed curves. Wang et al. [9] has demonstrated that the GaAsP material has a bandgap range of 1.65–1.67 eV, which corresponds to a wavelength between 742 nm and 751 nm. In this paper, the J_{sc} of the SiGe bottom cell was integrated from photons with wavelength longer than 750 nm. If all photons with wavelength shorter than 750 nm were absorbed by the GaAsP top cell, the density of the collectable current is 24.5 mA/cm^2 under AM1.5G spectrum. The matched J_{sc} of the dual junction device is proposed to be 21.0 mA/cm^2, with the optical and electrical losses considered.

To reach the target J_{sc} while minimizing the V_{oc} loss, it is concluded that the Ge composition should be controlled below 88% [13]. This Ge composition corresponds to a bandgap of 0.805 eV and a wavelength of 1540 nm. This allows an equivalent current density of 29.5 mA/cm^2, to be absorbed by the SiGe bottom cell. In practice, not all photons with energy beyond the $Si_{(1-x)}Ge_{(x)}$ bandgap can be absorbed. The absorption of photons is a function of the material absorption coefficient and optical path length. To calculate the practical current density, we firstly counted the absorbed photons that available to generate carriers in the semiconductor. The current density integrated from the absorbed photons with wavelength longer than 750 nm is defined as J_A in

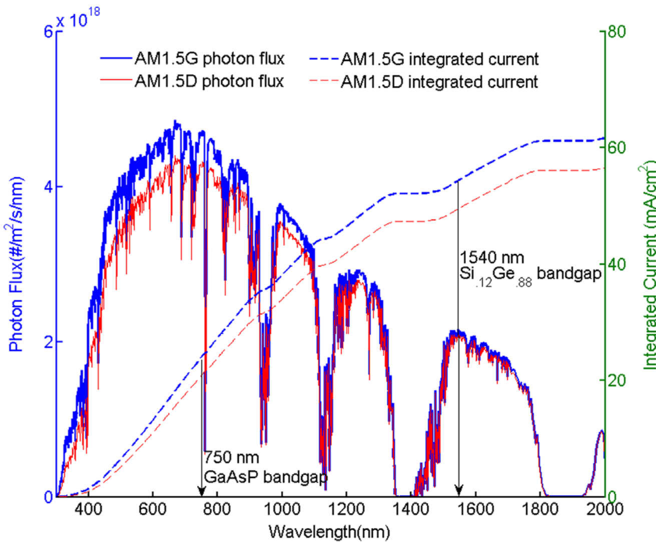

Fig. 1. Photon flux at AM1.5G spectrum (1000 W/m^2) or AM1.5D spectrum (900 W/m^2) as a function of wavelength. The dashed curves plot the cumulative short circuit current density by calculating the integral of the photon flux at each wavelength.

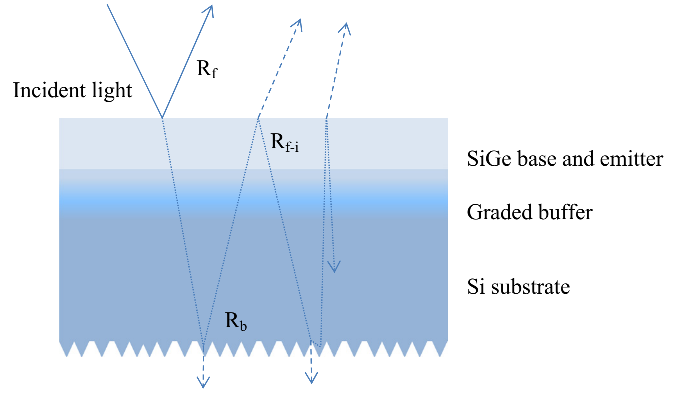

Fig. 2. Simplified optical paths in the SiGe structure.

Eq. (1). The simplified optical paths in the structure are sketched in Fig. 2.

$$J_A = \sum q \int_{\lambda_1}^{\lambda_2} \frac{n_1(\lambda)\varphi(\lambda)}{E_{ph}(\lambda)} \times A(\lambda \Bigg) d\lambda \quad (1)$$

where $\varphi(\lambda)$ is the spectral irradiance from the sun, $E_{ph}(\lambda)$ is the photon energy, C is the light concentration; and $A(\lambda)$ is the ratio of the number of absorbed photons to the total number of incident photons at λ wavelength. $A(\lambda)$ is determined by the material's absorption coefficient [5,14,15], the layers' thicknesses, the reflectance and equivalent optical path length of light. To calculate the corresponding J_A from absorbed photons, the following assumptions have been used: 5% front reflection (R_f), 95% back reflection (R_b), 93% front internal reflection ($R_{f\text{-}i}$) [13], 100% collection probability of generated carriers. An R_b of 95% and an R_f of 5% were chosen, based on the practical values that can be achieved by implementing a good silicon dioxide (SiO_2) back surface reflector between the Si-Al interface, and by depositing multi-layer anti reflection coating at the front surface [16–18]. As for the $R_{f\text{-}i}$, achieving perfect Lambertian reflection can be represented with a $R_{f\text{-}i}$ of 93% for the same device [13]. Table 1 lists the calculated J_A from structures with varied Ge concentration, and base thicknesses.

If the device operates with the ideal case, the density of available current to be collected by $Si_{(1-x)}Ge_{(x)}$ cells with 5 μm base and 250 nm emitter for 82% Ge, 85% Ge and 88% Ge are 19.4 mA/cm^2, 23.3 mA/cm^2 and 24.4 mA/cm^2, respectively. If the base thickness is reduced from 5 μm to 2 μm, the current density decreases by 1.2–1.9 mA/cm^2.

The calculated J_A from Eq. (1) represents the density of the total amount of current that can be collected by the solar cell. It does not account in the carriers' real collection probability. In order to analyze the cell performance in practice and predict the achievable J_{sc} by varying the cell design, a one-dimensional model is introduced [19]. In a practical case, Eq. (1) can be expanded as Eqs. (2)–(8). These equations account in the following parameters: optical reflection, photon absorption of each layer, and collection probability $f(x)$ of photo-generated carriers at different positions. The difference between Eqs. (1) and (2) is that Eq. (2) accounts in

Table 1
Current density integrated from absorbed photons with wavelength longer than 750 nm for cells of different Ge concentrations and base thicknesses.

Structure	82% Ge 2 μm base	85% Ge 2 μm base	88% Ge 2 μm base
J_A (mA/cm^2)	18.2	21.4	22.7
Structure	82% Ge 5 μm base	85% Ge 5 μm base	88% Ge 5 μm base
J_A (mA/cm^2)	19.4	23.3	24.4

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