Numerical Analysis of a Solar Cell with a Tensile-Strained Ge as a Novel Narrow Band Gap Absorber

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1. Introduction

Over-40% conversion efficiency has been achieved using 3-junction concentrator cells [1]. In the future, the 5- or 6-junction cells are required for realizing still higher efficiency. Tensile-strained (TS) Ge is a promising material for the bottom cell absorber material in such cells which can effectively absorb low-energy (<1.0 eV) photons. It is expected that the direct band gap of Ge shrinks faster than the indirect gap by applying biaxial tensile strain, which suggests the drastic increase of absorption coefficient in the low-energy region [2]. In addition, its "adjustable" lattice constant offers new degrees of freedom in designing and fabricating multijunction (MJ) cells. The direct band gap narrowing of Ge by small (<0.6%) amount of tensile strain has been experimentally confirmed using thermal mismatch between Si and Ge, and mechanical tensile strain technology [3, 4]. Much highly TS Ge films have been grown on $Ge_{1-x}Sn_x$ and $In_xGa_{1-x}As$ virtual substrates [5-7]. Using the latter technology, the amount of tensile strain is controlled from 0.40 to 1.55% by changing the In mole fraction in $In_xGa_{1-x}As$ layers [7]. This result suggests the usefulness of TS Ge as a bottom cell absorber in MJ cells, particularly, in inverted-grown cells [1]. In this paper, we numerically demonstrate the possibility of TS Ge as a novel narrow band gap absorber in thin, low-cost, and high-efficiency MJ solar cells.

2. New structure for a Novel Narrow Band Gap Absorber and Simulation Methods

The new structure we propose for the novel bottom absorber in MJ cells is the following: A p-type (10^{16} cm^{-3}) TS Ge layer is sandwiched between lattice-matched 50nm n (10^{16} cm^{-3}) and p^{++} (10^{20} cm^{-3}) $In_xGa_{1-x}As$ layers. This double-hetero (DH) structure can produce both the large open-circuit voltage (V_{oc}) and the short circuit current (J_{sc}) [8]. We simulated the solar cell operation of the DH structure using the package Afors-Het. To demonstrate the operation as a bottom cell in MJ cells, the intensity of sunlight in high-energy region (>1.1 eV), which is absorbed in other higher band gap subcells, was assumed to be zero. The absorption spectra $\alpha(E)$ of TS Ge were approximated as $\alpha(E)= A_L(E-E_{gL})^2/E +A_\Gamma(E-E_{g\Gamma})^{1/2}/E$, where E_{gL} and $E_{g\Gamma}$ are the indirect and direct band gap of TS Ge. E_{gL} and $E_{g\Gamma}$ were expressed as $E_{gL}= 0.668-0.145\varepsilon$ and $E_{gG}= 0.807-0.229\varepsilon$, where ε is the strain (%) in TS Ge film [2].

Band-to-band recombination process, which seldom dominates the recombination process of indirect transition semiconductors such as Si and Ge, must be considered in TS Ge because the band structure of Ge "approaches direct transition structure" by tensile strain. We have determined "effective band-to-band recombination coefficient" of $B_{eff}=(1-x)B_L+xB_\Gamma$, where B_L and B_Γ are the indirect and direct band-to-band recombination coefficient of Ge. Here, x represents the electron occupation ratio of direct and indirect conduction band valleys. By including the band-to-band and Auger recombination process, the lifetime of unstrained Ge becomes around 50µs, which is reasonable compared to the experimental result and confirms the validity of a series of the simulations.

3. Results and Discussions

Table I: The calculated solar cell performances of the DH cell and bulk Ge cell.

	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF(%)	Eff. (%)
0% Ge DH	508	3.14	82.5	1.32
1% Ge DH	362	8.25	75.7	2.26
bulk Ge	266	14.81	68.2	2.69

Table I shows the calculated solar cell performances of the $In_{0.01}Ga_{0.99}As$/ unstrained Ge (500nm)/ $In_{0.01}Ga_{0.99}As$ cell and the $In_{0.15}Ga_{0.85}As$/ 1.0%-TS Ge (500nm)/ $In_{0.15}Ga_{0.85}As$ cell (named "0% Ge DH" and "1% TS Ge DH", respectively) under 50-sun (<1.1 eV). The reference results of a bulk Ge cell (100nm n^{++}-Ge/ 300µm p-Ge/ 1µm p^{++}-Ge) are also shown. The V_{oc} of 0% Ge DH and 1% TS Ge DH cell is higher than that of the bulk Ge cell, showing the effect of employing the DH structure. The efficiency of 1.0% TS Ge DH cell is comparable to that of the bulk Ge cell, although their total thickness is about a five hundredth part of that of the bulk Ge cell. This result comes from the absorption enhancement of Ge by tensile strain.

When we increase the tensile strain in the TS Ge, the J_{sc} increases due to the absorption enhancement and the V_{oc} decreases due to the band gap narrowing. Therefore, there is an optimum range of tensile strain by which the DH structure produces the best conversion efficiency. Figure 1 shows the dependence of the efficiency of the DH cells on the tensile strain and the thickness of the TS Ge layers. The bulk Ge cell efficiency (2.69%) with a thickness of 300µm

is also indicated. By applying over-0.5% tensile strain, around 700nm TS Ge DH cells produce the same efficiency as that of the bulk Ge cell. The critical thickness of TS Ge film is also shown in Fig.1 [9]. The region where the DH cell can overcome the efficiency of bulk Ge cell within the critical thickness ranges the tensile strain of 0.2-0.5% and the thickness of 700-1000nm. It is rather narrow and does not exist in 0.5%-1.0% tensile strain region. Since this DH structure is used for the bottom cells in MJ cells, we can utilize the rear electrodes as the reflection films. The conversion efficiency and current density of the DH structure can be further improved using the rear reflection so that much thinner TS Ge can produce sufficient conversion efficiency. Similar results are obtained under high concentration ratio, for example, 200-sun.
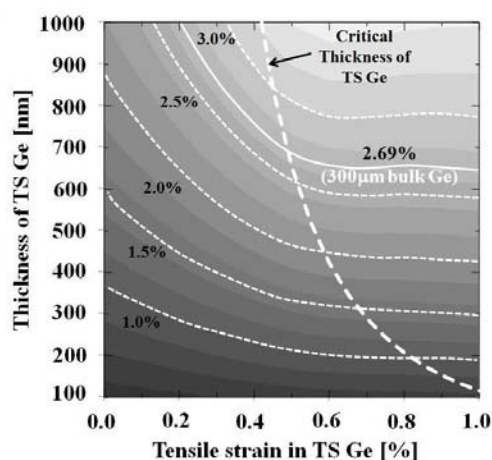

Fig. 1 The dependence of the efficiency (%) of the DH cells on the tensile strain and the thickness of the TS Ge layers under 50-sun (<1.1 eV).

One major advantage of using TS Ge is offering new degrees of freedom in designing and fabricating the MJ cells. Figure 2 shows the design examples of 5 junction lattice-matched MJ cells using the 300nm 0.5%, 0.7%, and 1.0% TS Ge DH structure or 300μm unstrained Ge substrate (named "0.5% line", "0.7% line", "1.0% line", and "0% line" in the figure, respectively). These cells use $In_x Ga_{1-x}As$ as second cells. The conversion efficiencies of the 0.5%, 0.7% and 1.0% TS Ge line cells are higher than that of the 0% line cell, which shows the one of the advantages of using TS Ge. The thicknesses of 0.5% and 0.7% TS Ge cells are within the critical thickness and the conversion efficiencies of these cells are comparable to that of the optimum one (55.26%) which composes 2.17/ 1.73/ 1.42/ 1.16/ 0.93 eV band gap subcells. These results show that using TS Ge offers new degrees of freedom about lattice-matching and sunlight splitting in designing and fabricating MJ cells compared to using unstrained Ge substrate as bottom cells. In addition, it drastically (~1/100) reduces the expensive Ge usage. Therefore, the $In_x Ga_{1-x}As$ /TS Ge/ $In_x Ga_{1-x}As$ structure is found to be promising for novel bottom cell absorbers in future MJ cells.
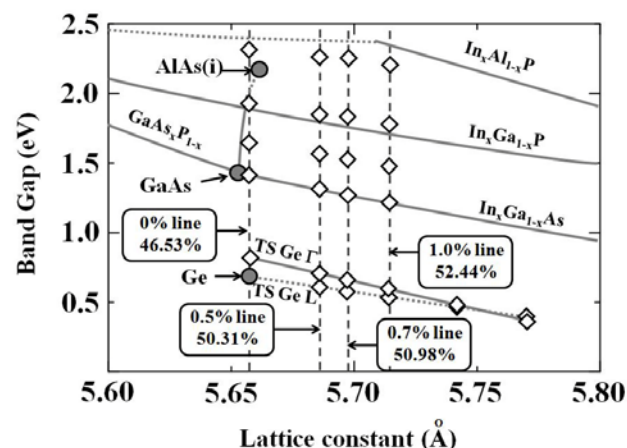

Fig. 2 The design examples of 5 junction lattice-matched MJ cells using the TS Ge DH structure as bottom cells under 50-sun. the "TS Ge Γ" and "TS Ge L" lines show the dependence of the direct and indirect energy gaps of TS Ge on lattice constant. The diamonds on vertical broken lines indicate material combinations. In 0%, 0.5%, 0.7%, and 1.0% line cells, the bottom cells absorb photons in 1.40-0.67, 1.30-0.60, 1.26-0.57, and 1.21-0.52eV region, respectively.

4. Conclusions

The $In_x Ga_{1-x}As$ / tensile-strained (TS) Ge/ $In_x Ga_{1-x}As$ double-hetero (DH) structure utilizing TS Ge as a light absorber has been proposed for realizing thin and lattice-adjustable bottom cells in future multijunction (MJ) solar cells. It has been found that the efficiency same as or greater than that of a 300 μm bulk Ge cell can be realized with sub-μm 0.5~1.0% TS Ge. The design examples of high-efficiency lattice-matched 5 junction cells using tensile-strained Ge as bottom cells are also demonstrated. Using TS Ge drastically reduces the expensive Ge usage and offers new degrees of freedom in designing MJ cells. Therefore, the new TS Ge cell structure we propose is an ideal for novel bottom cell in next-generation MJ cells.

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