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First demonstration of $BaSi_2$ pn homojunction solar cell

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Abstract

In this study, we aimed to confirm the operation of a $BaSi_2$ homojunction solar cell. To this end, we formed two types of solar cells for comparison, that is Sb-doped n^+-$BaSi_2$/p-Si heterojunction solar cell and Sb-doped n^+-$BaSi_2$/B-doped p-$BaSi_2$ homojunction solar cell. Under AM 1.5 illumination, it was demonstrated from the internal quantum efficiency spectrum of the homojunction diode, photogenerated carriers were originated from the p-$BaSi_2$ layer and they were separated by the built-in electric field of the pn junction. This is the first demonstration of a $BaSi_2$ homojunction solar cell.

1. Introduction

We have paid special attention to semiconducting $BaSi_2$ because $BaSi_2$ has attractive features as solar cell material from the viewpoint of a bandgap of 1.3 eV, a large absorption coefficient $\alpha = 3 \times 10^4$ cm^{-1} at 1.5 eV, and a large minority-carrier lifetime $\tau \sim 10$ μs, giving a large minority-carrier diffusion length $L \sim 10$ μm, which is sufficiently large for thin-film solar cell applications [1]. Recently, we have achieved an efficiency $\eta = 9.9\%$ in B-doped p-$BaSi_2$/n-Si heterojunction solar cells [2]. But the open-circuit voltage V_{OC} was smaller than 0.5 V because the built-in potential of p-$BaSi_2$/n-Si is limited up to 0.2 eV. Therefore, to achieve the high efficiency solar cells, $BaSi_2$ homojunction solar cells are necessary. An $\eta > 25\%$ with an open-circuit voltage > 0.8 V can be expected in a $BaSi_2$ homojunction solar cell [3]. Furthermore, we can target $BaSi_2$-pn/Si-pn tandem solar cells to achieve $\eta > 30\%$.

Contact resistance is one of the most important parameters that directly affects the η. In our previous work, contact resistance reached a minimum of 0.019 Ω·cm^2 in Al/Sb-doped n-$BaSi_2$, which is much smaller than that in Al/B-doped p-$BaSi_2$ [4]. That's why we chose the structure where n-$BaSi_2$ was positioned at the surface side. Furthermore, we plan to use undoped $BaSi_2$ as an active layer of a $BaSi_2$ homojunction solar cell like sample A in Fig. 1(a). This is because undoped $BaSi_2$ has a large L, and this feature facilitates the collection of photogenerated carriers in an external circuit even though L degrades to some extent owing to extrinsic effects such as crystal imperfections and other causes. As a first step, however, we attempted to form samples B, C and D to confirm the operation of a solar cell. In this work, we first aimed to confirm the operation of a $BaSi_2$ homojunction solar cell.

2. Experiment

Schematics of solar cell samples are shown in Figs. 1(a)-(c). Sample A is ideal; however, we formed samples B, C and D to confirm the operation of a solar cell. In sample B, Sb-doped n-$BaSi_2$(300 nm, n~10^{19} cm^{-3}) was formed on medium doped p-Si(111) ($\rho > 0.1$ Ωcm) by molecular beam epitaxy (MBE). On the other hand, in samples C and D, Sb-doped n-$BaSi_2$(50 nm, n~10^{19} cm^{-3})/B-doped p-$BaSi_2$(500 nm, p~10^{16} or 10^{17} cm^{-3})/B-doped p-$BaSi_2$(20 nm, p~10^{19} cm^{-3}) was formed on low-resistivity p-Si(111) ($\rho < 0.01$ Ωcm) by MBE. The difference of sample C and D is the hole concentration of the p-$BaSi_2$ absorber layer, p~10^{16} for sample C and 10^{17} cm^{-3} for sample D. Using such a low-ρ Si substrate, we can eliminate the contribution of photogenerated carriers in the Si substrate. These substrates have defects at the $BaSi_2$/Si interface caused by step-bunching upon the thermal cleaning of the Si substrate [5]. So high-η is not expected, but we use this substrate to achieve the purpose of this study. For all the samples, a 3-nm-thick a-Si passivation layer was deposited [6]. Finally, 80-nm-thick ITO surface electrode and 150-nm-thick Al back electrode were made by sputtering. The crystallinity was investigated using θ-2θ XRD and RHEED. The photoresponse properties and current density versus voltage (J-V) characteristics were measured at room temperature under AM 1.5 illumination.

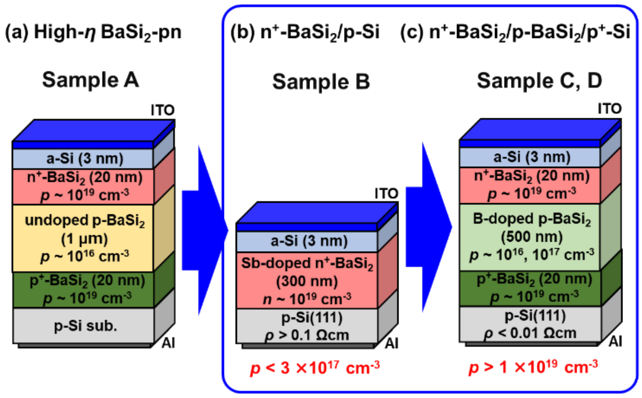

Fig. 1 Schematics of samples.

3. Results and discussion

Figures 2 and 3 show (a) the θ-2θ XRD and (b) RHEED for sample B and D, respectively. The XRD patterns show both samples contain a-axis-oriented $BaSi_2$ epitaxial films. From the RHEED patterns, streaky patterns are obtained after the deposition of every $BaSi_2$ layer and halo patterns are obtained after the deposition of a-Si layers.

Figs. 4(a)-(b) show the J-V characteristics and IQE spectrum of sample B. Rectifying properties was obtained.

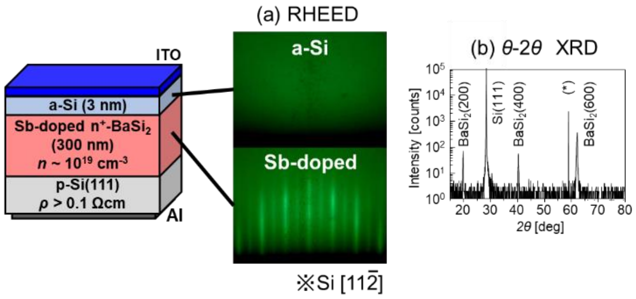

Fig. 2 (a) RHEED and (b) XRD patterns of sample B, Sb-doped n-$BaSi_2$(300 nm, $n \sim 10^{19}$ cm^{-3})/p-Si(111) ($\rho > 0.1$ Ωcm) heterojunction solar cell.

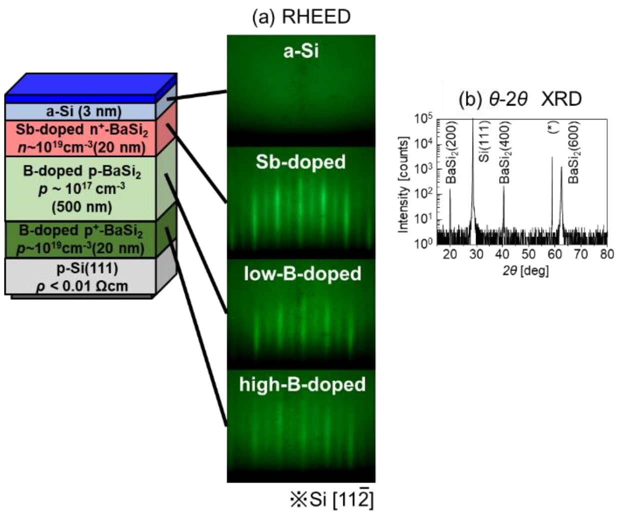

Fig. 3 (a) RHEED and (b) XRD patterns of sample D, Sb-doped n$^+$-$BaSi_2$(20 nm, $n \sim 10^{19}$ cm^{-3})/B-doped p-$BaSi_2$(500 nm, $p \sim 10^{17}$ cm^{-3})/B-doped p$^+$-$BaSi_2$(20 nm, $p \sim 10^{19}$ cm^{-3})/p$^+$-Si(111) ($\rho < 0.01$ Ωcm) homojunction solar cell.

A short-circuit current density J_{SC} = 11.8 mA/cm^3, an open-circuit voltage V_{OC} = 0.22 V, a series resistance R_S = 148 Ω, and η = 1.5% were obtained. The values of J_{SC}, V_{OC} and η are much smaller than those obtained in B-doped p-$BaSi_2$/n-Si heterojunction solar cells [6]. This is because there are large conduction-band and valence-band offsets at the n-$BaSi_2$/p-Si interface, which hinder the transport of photogenerated carriers. As shown in Fig. 4(b), the internal quantum efficiency (IQE) increases sharply at wavelengths λ < 1200 nm, corresponding to the band gap of Si. On the other hand, the *IQE* is negligibly small in the short wavelength range λ < 600 nm. This means that the photogenerated carriers in the 300-nm-thick n$^+$-$BaSi_2$ do not contribute to the photocurrent.

Figures 5(a) and 5(b) show the *J-V* characteristic of sample D and *IQE* spectra of samples C and D. The leakage current is so large in Fig. 5(a); however, rectifying properties is also obtained. In sample D, the *IQE* exceeded 30% at a wavelength λ of 500 nm. The *IQE* increases sharply at wavelengths λ < 700 nm in Fig. 5(b), while the *IQE* in the long wavelength range is very small. Considering that the absorption length (3/α) at λ=500 nm is approximately 0.1 μm in $BaSi_2$, we can state that the

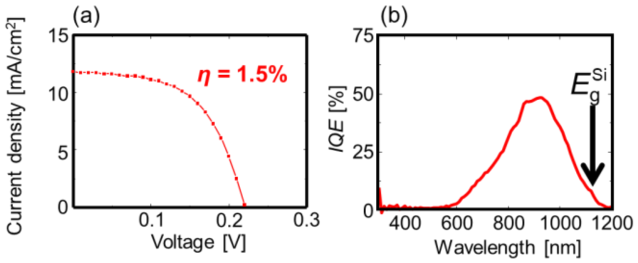

Fig. 4 (a) *J-V* characteristics and (b) *IQE* spectrum of sample B.

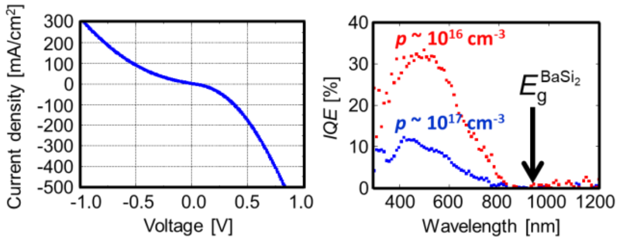

Fig. 5 (a) *J-V* characteristics of sample D and (b) *IQE* spectrum of samples C and D.

photogenerated carriers were separated by the electric field of the $BaSi_2$ pn junction diode in samples C and D. This is the first demonstration of a $BaSi_2$ homojunction solar cell. The η is very small at the moment because of large leakage currents, which are originated from defects at the $BaSi_2$/Si interface caused by step-bunching [5]. The η will be improved very soon by using an epitaxial p$^+$-Si layer on p-Si.

4. Conclusions

We demonstrated the operation of a $BaSi_2$ pn homojunction solar cell in Sb-doped n$^+$-$BaSi_2$(20 nm, $n \sim 10^{19}$ cm^{-3})/B-doped p-$BaSi_2$(500 nm, $p \sim 10^{16}$, 10^{17} cm^{-3})/B-doped p$^+$-$BaSi_2$(20 nm, $p \sim 10^{19}$ cm^{-3}) on p$^+$-Si(111) ($\rho < 0.01$ Ωcm) for the first time. The rectifying properties were obtained in the *J-V* characteristics though the leakage current was significantly large. From the *IQE* spectrum that increased sharply at λ < 700 nm, we can conclude that the photogenerated carriers were separated by the built-in electric field of the $BaSi_2$ pn junction. This is the first demonstration of $BaSi_2$ pn homojunction diode.

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