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Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp1172-1173

Engineering of Energy Band Structure with Epitaxial $Ge_{1-x-y}Si_xSn_y$/n-Ge Hetero Junctions for Solar Cell Applications

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Abstract

We prepared $Ge_{1-x-y}Si_xSn_y$/Ge hetero junction structures and investigated its electrical and optoelectrical properties for high efficiency solar cell applications. We demonstrated the modulation of the energy band gap of a $Ge_{1-x-y}Si_xSn_y$ layer which is epitaxially grown with its lattice constant well matches to Ge.

1. Introduction

There are many efforts to improve on current generation efficiency of solar cells. The maximum value of the theoretical efficiency is expected to be less than 30% for Si based single junction solar modules commonly used [1]. On the other hand, multi junction solar cells are able to enhance the efficiency because of appropriate energy band gap adjustment for the solar spectrum. The efficiency of 36% has been achieved by using InGaP(1.9eV)/InGaAs(1.4eV)/Ge(0.7eV) three junction cell [2]. Furthermore, a four junction cell with an absorption interlayer whose bandgap is 1.0 eV promises the efficiency over 40% [3].

In this study, we focused $Ge_{1-x-y}Si_xSn_y$ ternary alloy to realize multi junction cell with group-IV semiconductor materials. $Ge_{1-x-y}Si_xSn_y$ is an attractive material because both its lattice constant and band gap can be tuned independently with adjusting Si and Sn compositions. The energy band gap can be controlled from 0.66 eV of Ge to 1.1 eV as well as Si with a lattice constant matching to Ge [4]. Beeler *et al*. reports the photo response of a $Ge_{1-x-y}Si_xSn_y$ layer with a Sn content less than 4% [5]. In this study, we focus the target Si and Sn contents of 24% and 7.0%, respectively, in order to obtain the band gap of 1.0 eV with the lattice constant matching to Ge substrate. We demonstrated the energy band gap modulation from electrical and photo response properties.

2. Sample preparation

A chemically cleaned n-type Ge(001) substrate was loaded into the ultra high vacuum chamber and the clean surface was confirmed with RHEED pattern after thermal annealing. A 200 nm-thick undoped Ge or $Ge_{0.69}Si_{0.24}Sn_{0.07}$ layer was epitaxially grown at 150°C with molecular beam epitaxy (MBE) method. Then, a mesa-shaped structure was formed with wet etching. A 300 nm-thick SiO_2 layer was deposited with coating of spin-on-glass and annealing at 450°C. Finally, contact holes are formed and an Al grid electrode was deposited to take incident light (Fig. 1).

3. Results and discussion

Figure 2 shows a result of x-ray two dimensional reciprocal space mapping (XRD-2DRSM) for an as-grown $Ge_{0.69}Si_{0.24}Sn_{0.07}$ layer on Ge(001). We can confirm pseudomorphic growth with no strain relaxation of $Ge_{0.69}Si_{0.24}Sn_{0.07}$ on Ge. Thickness fringe is clearly observed, indicating that an abrupt interface is formed.

I-V characteristics of the undoped Ge/n-Ge and undoped $Ge_{0.69}Si_{0.24}Sn_{0.07}$/n-Ge diodes were measured at various temperatures from 100K to 360K (Fig. 3). Both samples exhibit good rectifying property of pn junction despite epitaxial layers are grown with undoped condition. As is often with undoped Ge grown with low temperature MBE, epitaxial Ge and $Ge_{1-x-y}Si_xSn_y$ layers exhibit p-type conduction due to unintentional hole generation. We can observe leakage current limited by tunneling phenomenon at $Ge_{1-x-y}Si_xSn_y$/Ge hetero interface below 167K.

Figure 4 shows the Arrhenius plot of the reverse current above 310K for both samples to discuss the energy bandgap of epitaxial layers. In ideal situation, reverse current is expressed by $I_R \propto \exp[-E_g/mk_BT]$, where m varies from 1 to 2 depending on diffusion and generation carrier transport mechanisms, respectively. The activation energy, E_g/m of 0.69 eV estimated for the Ge/n-Ge diode agrees very well with the theoretical bandgap of bulk Ge. On the other hand, The energy bandgap for the $Ge_{0.69}Si_{0.24}Sn_{0.07}$/n-Ge sample is estimated to be 0.79 eV. Beeler *et al*. reports the activation energy of is less than 0.578 eV for $Ge_{1-x-y}Si_xSn_y$/Ge hetero junction [5]. The larger activation energy, E_g/m in this study indicates the increasing in the energy bandgap of $Ge_{1-x-y}Si_xSn_y$ with larger Si and Sn content, and/or the decreasing in the m value due to the improvement on the crystallinity of the epitaxial layer.

Figure 5 shows the external quantum efficiencies (E.Q.E) estimated with the photo response measurement. Excess current with incident light was observed for both samples at the energy larger than 0.66 eV. The origin of this absorption for the Ge/n-Ge samples can be accounted by Ge layer and Ge substrate. In addition, the value of E.Q.E. rises at the energy above 0.9 eV even though epitaxial $Ge_{0.69}Si_{0.24}Sn_{0.07}$ layer is very thin. This result evidently means that $Ge_{0.69}Si_{0.24}Sn_{0.07}$ has an energy bandgap as large as 0.9 eV.

4. Conclusions

We have demonstrated increasing the energy bandgap of $Ge_{1-x-y}Si_xSn_y$ layer pseudomorphically grown on Ge(001) substrate. The photo response measurement of $Ge_{1-x-y}Si_xSn_y$/Ge hetero junctions reveals that the energy bandgap above 0.9 eV is achieved by introducing Si of 24% and Sn of 7.0%.

Acknowledgements

This work was partly supported by the ALCA Program of JST, Japan. We acknowledge SOMA OPTICS Ltd. for their help of the photo response measurement.

References

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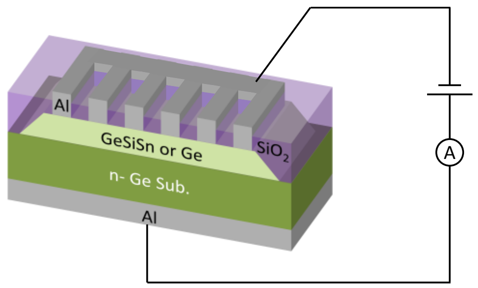

Fig1. Schematic diagram of the solar cell diode sample prepared in this study.

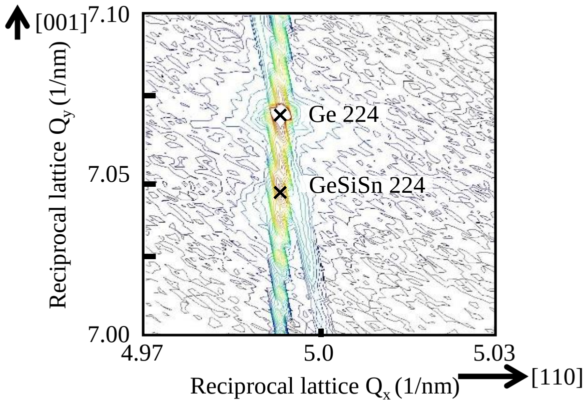

Fig2. XRD-2DRSM of as-grown $Ge_{0.69}Si_{0.24}Sn_{0.07}$

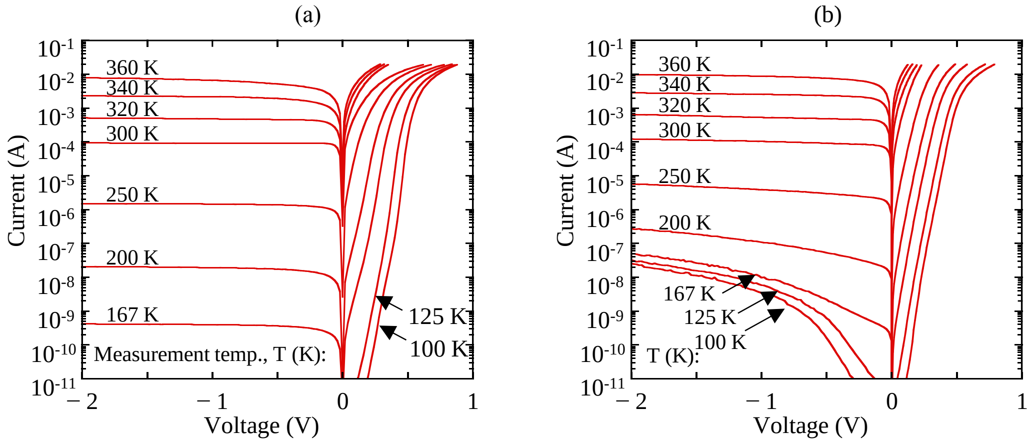

Fig.3 Forward and reverse I-V characteristics of solar cell diodes for various measurement temperatures. (a) Epitaxial-Ge/n-Ge and (b)Epitaxial-$Ge_{0.69}Si_{0.24}Sn_{0.07}$/n-Ge.

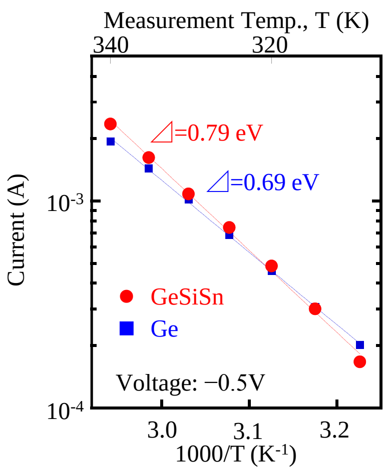

Fig.4 Arrhenius plot of the reverse current at 0.5 V reverse bias for Ge/n-Ge and $Ge_{0.69}Si_{0.24}Sn_{0.07}$/n-Ge samples.

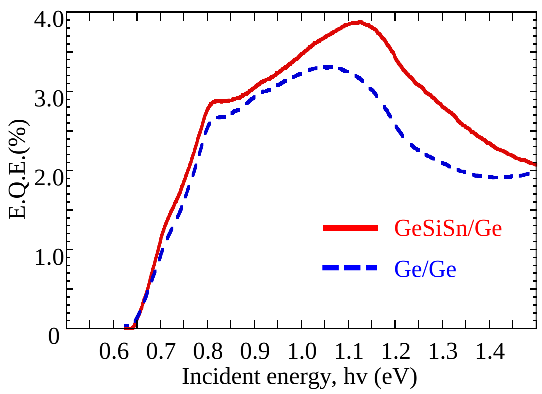

Fig.5 External quantum efficiency of undoped $Ge_{1-x-y}Si_xSn_y$/Ge and undoped Ge/n-Ge diodes at room temperature