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A novel approach to characterization of bottom sub-cell in multijunction solar cell using photoluminescence.

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Abstract. Multijunction solar cells grown on group IV substrates using III-V compounds are very promising due to their high efficiency (over 40%). Further development of these structures is mainly focused on III-V layers while bottom sub-cell based on p-n junction in the substrate is disregarded. However, high temperatures required for III-V epitaxy as well as diffusion over III-V/IV interface may affect minority carrier lifetime in the substrate. GaAs/GaInP/(AlAs)/Ge heterostructures were grown by MOCVD. Thermal annealing at the conditions of triple-junction solar cells was performed and photoluminescence spectra for these structures were investigated.

1. Introduction

Group IV substrates are widely used for photovoltaic applications because of their excellent electrical and mechanical properties. Multijunction III-V solar cells grown on Ge substrates are of the great interest due to their supreme efficiency that has already exceeded 46% [1]. The development of these structures is mainly focused on the optimization of III-V layers parameters while germanium sub-cell is disregarded. However, Ge sub-cell contributes up to 10% of total solar cell efficiency [2] but the properties of III-V interface are not studied enough. The p-n junction in bottom sub-cell is conventionally formed by the diffusion during epitaxial growth of III-V layers, thus the parameters of the sub-cell are dependent on the temperature and growth time. III-V epitaxy and especially top sub-cell based on GaInP requires high temperatures so the parameters of III-V/Ge interface alter during subsequent layers growth. Accordingly, direct characterization becomes complex because of the number of layers grown. We have previously shown that diffusion of group III atoms during epitaxial growth of III-V layers leads to the formation of undesirable potential barrier for charge carriers at the III-V/IV heterointerface [3]. Thus, charge carrier lifetime which depends on impurity level can be also affected by diffusion processes. In this paper the influence of III-V epitaxy on the minority carrier lifetime in Ge substrates is discussed.

2. Samples

Structure that represents bottom sub-cell (figure 1a) of multijunction solar cell was fabricated using Aixtron 200 MOCVD equipment. P-type Ga-doped (N_A = (2-4)·10^{17} cm^{-3}) germanium substrates <100> with 6º offcut toward <111> plane were used to ensure APD-free growth of epitaxial layers. Epitaxy of germanium can lead to a high level of background doping, thus 100 nm n-GaInP layer was grown on the substrate. The p-n junction was formed by the diffusion of P atoms into the substrate during epitaxial growth. The structure was capped with 300 nm n'-GaAs contact layer.

In order to suppress the simultaneous diffusion of group III atoms over III-V/IV interface another structure with thin AlAs layer was grown (figure 2b). AlAs is reported to be an efficient diffusion barrier [4]. The p-n junction in Ge is formed by As diffusion during AlAs nucleation process. High value of
Conduction band offset ($\Delta E_C = 0.3-0.5$ eV) [5] at the AlAs/Ge interface may affect charge carrier transport. AlAs layer was heavily doped with Te ($N_D > 10^{19}$ cm$^{-3}$) to ensure tunnelling through the barrier. This structure was also capped with 300 nm n$^+$-GaAs contact layer.

![Figure 1. Schematic representation of conventional Ge sub-cells (a) and the sub-cell with AlAs diffusion barrier (b).](image)

Both structures with and without AlAs layer exhibit close values of $V_{OC} = 0.2$V, however GaAs/AlAs/Ge demonstrate lower value of $I_{SC}$ (figure 2). The diffusion coefficient of As in Ge is higher than that of P [6] which results in thicker emitter and thus higher recombination rate of photogenerated electron-hole pairs.

![Figure 2. I-V curves for Ge sub-cell and the sub-cell with AlAs diffusion barrier.](image)

### 3. Experiment

For the study of solar cells, non-destructive research methods are preferable, since it is possible to control parameters of interest of the same structure during epitaxial growth. Minority carrier lifetime in Ge substrate can be estimated by different measurement techniques such as QSSPC [7], however the results obtained by it are not reliable at high doping levels (>10$^{17}$) of the substrates. Also, the top side of the substrate near III-V/IV heterointerface is of the most interest so the photoluminescence technique was used to investigate grown structures.

To verify the applicability of selected method a PL spectrum (figure 3a) was obtained for clean Ge substrate using 914nm laser diode. The substrate was preliminary passivated using HF to reduce recombination losses and increase PL intensity. PL peak was observed with a maximum around 1600 nm. This behaviour is related to InGaAs photodetector which has an absorption edge at 1800 nm. To demonstrate the possibility of obtaining a signal from a substrate in structures with grown III-V layers, thick 2000 nm layer of GaAs was formed on Ge substrate and PL spectrum was measured (figure 3b). Germanium peak was detected although it has lower amplitude. The signal in range of 1000-1400 nm was observed, which is related to defects in GaAs.
4. Results

Photoluminescence spectra measured for germanium sub-cells described in section 2 demonstrate the similar behavior with a slightly higher intensity for GaAs/AlAs/Ge structure (figure 4a) which can be explained by a smaller total thickness of III-V layers. Thus, no difference between the effect of P and As diffusion on minority carrier lifetime in the substrate was observed. However, high temperatures required for epitaxial growth of subsequent sub-cells of multijunction solar cells affect the diffusion over III-V/IV interface. To investigate the effect of triple-junction GaInP/GaAs/Ge solar cell growth in MOCVD process on substrate lifetime test structures were annealed under corresponding conditions (T = 500..700ºC, t > 1 hour). No significant change in PL intensity for conventional Ge sub-cell after thermal annealing was observed. However, the structure with AlAs barrier layer demonstrated PL intensity from Ge substrate and therefore a charge carrier lifetime drastically reduced. Presumably, this is caused by dopant dispersion from AlAs layer into the substrate.

5. Conclusion

A novel approach to characterization of bottom sub-cell in multijunction (GaInP/GaAs/Ge) solar cells was proposed. The ability to detect signal from germanium substrate through epitaxial III-V layers was demonstrated. The results on minority carrier lifetime obtained using photoluminescence technique were discussed.
6. Acknowledgments

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