Hybrid heterostructures and heterostructure devices fabricated by surface activated bonding technologies

Naoteru Shigekawa[1]*

[1] Graduate School of Engineering, Osaka City University, Osaka 558-8585, Japan
* shigekawa@elec.eng.osaka-cu.ac.jp

Abstract

Surface activated bonding (SAB) is successfully applied for fabricating hybrid heterostructures, which are made of semiconductors with different lattice constants, coefficients of thermal expansion, and crystal symmetries, such as GaAs/Si and 4H-SiC/Si systems. We find that their electrical properties are improved by a post-bonding annealing. Performances of hybrid InGaP/GaAs/Si triple-junction cells and the possibility of Si/SiC Schottky diodes are examined. SAB of diamond to Si is also discussed.

Introduction

Semiconductor heterostructures, which are fabricated using epitaxial growth technologies, have been widely applied for various types of electrical and optical devices with excellent performances. Low-temperature direct wafer bonding technologies can provide a practical solution in making heterostructures composed of semiconductors with different lattice constants, coefficients of thermal expansion, and crystallographic symmetries, or hybrid heterostructures [1].
Junctions of dissimilar materials have been fabricated by using surface activated bonding (SAB) technologies [2]. In SAB, samples are bonded to each other at low temperatures just after removing native oxide layers on their surfaces, i.e., by activating their surfaces. A fast atom beam (FAB) of Ar is typically used in removing the native oxide layers.
Using SAB, we have fabricated various heterostructures. We have also explored the possibility for realizing novel advanced devices based on these heterostructures. In this presentation we discuss the characteristics of Si (001)/GaAs (001) [3-5] and Si (001)/4H-SiC (0001) [6,7] heterostructures with emphasis on their response to post-bonding annealing. Recent results of SAB of diamond [8] are also presented.

GaAs/Si heterostructures applied for hybrid tandem solar cells

We fabricated pn junctions by bonding GaAs and InGaP epi substrates and Si substrates with different polarities and impurity concentrations and measured their current-voltage (I-V) characteristics [3]. The relationship between their resistance and effective impurity concentration is shown in Fig. 1(a). I-V characteristics of n^+-GaAs (1×10^{19} cm^{-3})/n^+-Si (2.6×10^{19} cm^{-3}) heterostructures annealed at different temperatures [4] are shown in Fig. 1(b). The dependence of resistance on annealing temperature is shown in its inset. We obtained lower resistance in junctions with more heavily-doped bonding layers (Fig. 1(a)) annealed at higher temperatures (Fig. 1(b)). Thinner depletion layers at heterointerfaces were likely to bring about the reduction of resistance in pn junctions with more heavily-doped bonding layers. The decrease in resistance due to the annealing was related to the recrystallization of an amorphous-like layer that had been formed at the as-bonded GaAs/Si interface.

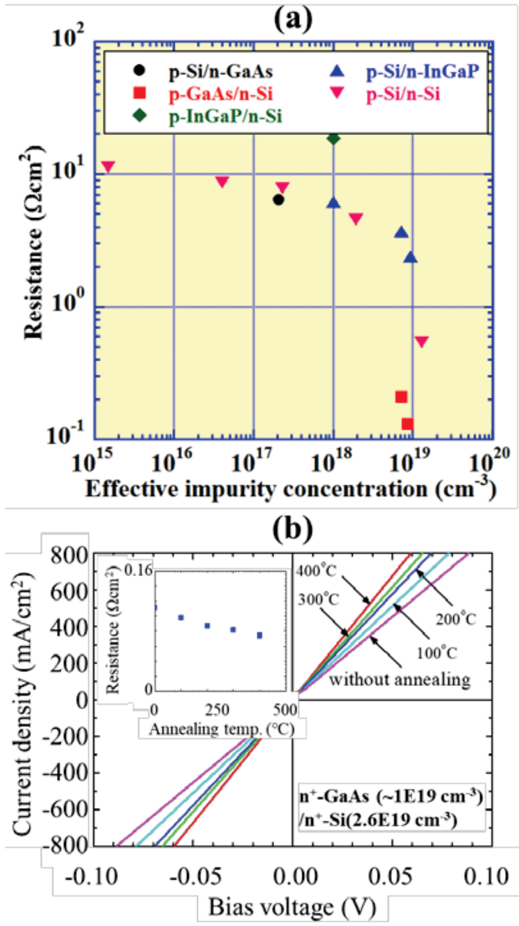

Figure 1. (a) Resistances across bonding interfaces of pn junctions with different impurity concentrations. (b) I-V characteristics of n-Si/n-GaAs heterostructures with different annealing temperatures. Relationship between resistance and annealing temperature is shown in the inset.

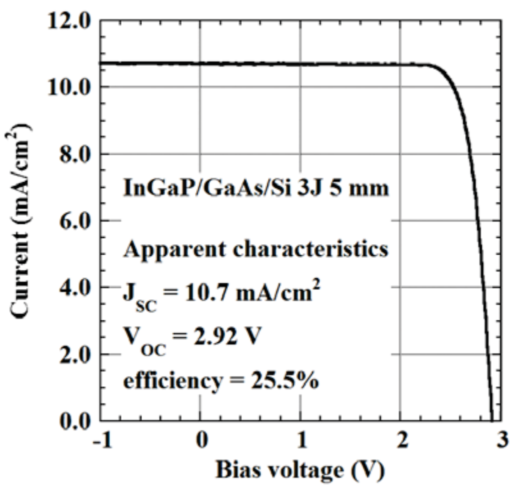

Figure 2. The I-V characteristics of a 5-mm-by-5-mm InGaP/GaAs/Si 3J cell under the solar irradiance.

We fabricated n-on-p InGaP/GaAs/Si hybrid triple-junction (3J) cells by SAB of InGaP/GaAs double-junction (2J) structures grown on GaAs (100) substrates and Si bottom cells, removal of GaAs substrates, and device fabrication process [5]. The bonding interface was made of heavily-doped GaAs and Si layers. I-V characteristics of a 5-mm-by-5-mm 3J cell are shown in Fig. 2. The cell revealed a conversion efficiency of ~25.5%. Contributions of the respective sub cells were confirmed by measuring their spectral response. Higher efficiencies are likely to be obtained by improving the performances of Si bottom cells and electrical characteristics of bonding interfaces. The resistance across the bonding interface in 3J cells was lowered by introducing an ITO film as intermediate layer [9].

Si/SiC heterostructures with high thermal tolerance

We fabricated and characterized n^+-Si/n-4H-SiC and p^+-Si/n-4H-SiC heterostructures by bonding heavily-doped p^+-Si (100) and n^+-Si (100) substrates to an n-SiC epi layer grown on an n^+-4H-SiC (0001) substrate [6]. The concentration of impurities of n-SiC layer was ~5×10^{15} cm^{-3}.
I-V characteristics of n^+-Si/n-SiC heterostructures before annealing and after annealing at 700 °C are shown in Figs. 3(a) and 3(b), respectively. The reverse-bias current was more sensitive to the ambient temperature and that at room temperature was lowered in the 700-°C annealed junction. The ideality factor at room temperature was improved by the annealing. Similar behaviors were observed in I-V characteristics of p^+-Si/n-SiC heterostructures.

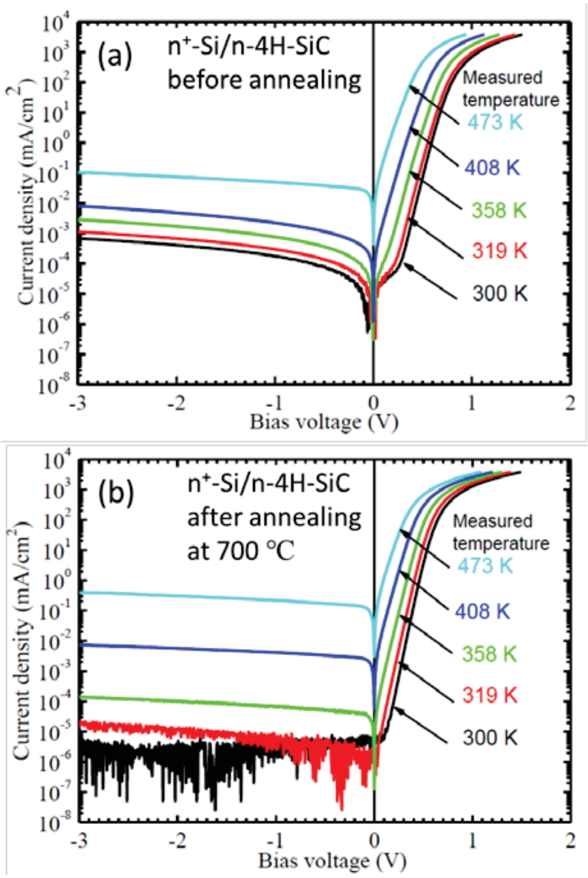

Figure 3. The I-V characteristics of n^+-Si/n-4H-SiC heterostructures (a) before annealing, and (b) after annealing at 700 °C.

Lower reverse-bias currents at room temperature due to annealing at higher temperatures indicate that the electrical properties of Si/SiC interfaces are improved by the annealing similarly to GaAs/Si interfaces discussed above. This view is supported by the result that the activation energy of the reverse-bias current was larger for a higher annealing temperature (not depicted).
Practically the obtained results suggest that SAB-based Si/SiC heterostructures are promising in realizing Schottky diodes with high thermal tolerance. We also fabricated HBT structures with SiC emitter and Si base and collector [7]. We obtained a current gain of ~10, which mean that minority electrons can be injected across the bonding interfaces.

SAB of diamond

An HPHT single-crystal diamond was successfully bonded to a Si substrate by optimizing the SAB conditions [8]. An SEM image of a diamond/Si interface is shown in Fig. 4. We also performed a TEM/EELS observation of the diamond/Si interface as well as an XPS characterization of a diamond surface exposed to an FAB of Ar. The obtained results suggested that the surface of diamond was damaged due to the irradiation of Ar beams so that a diamond-like-carbon layer was formed. It was assumed that such a layer played an important role in achieving diamond/Si junctions. The obtained results suggest that SAB of diamond could be applicable for preparing low-thermal-resistance modules that handle high electric powers.

Conclusions

We discussed application of surface activated bonding (SAB), one of the low-temperature direct bonding technologies, for fabricating hybrid heterostructures such as GaAs/Si and Si/SiC systems. We found that their electrical properties were improved by the post-bonding annealing. Performances of InGaP/GaAs/Si hybrid triple-junction solar cells and diode characteristics of Si/SiC heterostructures were demonstrated. The direct bonding of a single crystal diamond to a Si substrate was also mentioned. It was suggested that SAB was promising for fabricating advanced semiconductor devices and modules.

Acknowledgments

The work related to GaAs/Si and Si/SiC heterostructures was supported by “Creative research for clean energy generation using solar energy”program of Japan Science and Technology Agency (JST). A part of the work related to InGaP/GaAs/Si triple-junction cells was supported by the “Research and Development of ultra-high efficiency and low-cost III-V compound semiconductor solar cell modules (High efficiency and low-cost III-V/Si tandem)”project of New Energy and Industrial Technology Development Organization (NEDO). InGaP/GaAs double-junction-cell structures were supplied from Sharp Corporation. Research on bonding of diamond was supported by the Grant-in-Aid for Challenging Exploratory Research (16K13676) of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan.

References

[1] O. Moutanabbir and U. Gösele, Annu. Rev. Mater. Res. **40**, 469 (2010).
[2] E. Higurashi, Jpn. J. Appl. Phys. **57**, 04FA02 (2018).
[3] J. Liang, et al. Elec. Lett. **49**, 830 (2013).
[4] J. Liang, et al. Jpn. J. Appl. Phys. **54**, 030211 (2015).
[5] N. Shigekawa, et al. Jpn. J. Appl. Phys. **54**, 08KE03 (2015).
[6] J. Liang, et al. J. Appl. Phys. **120**, 034504 (2016).
[7] N. Shigekawa, et al. Jpn. J. Appl. Phys. **57**, 02BE04 (2018).
[8] J. Liang, et al. Appl. Phys. Lett. **110**, 111603 (2017).
[9] N. Shigekawa, et al. IEEE J. Photovoltaics (early access). DOI: 10.1109/JPHOTOV.2018.2802203