

# High-electron-mobility InAs thin layers down to $\sim 100$ nm obtained by epitaxial lift-off and normal/inverted van der Waals bonding on flexible substrates

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## 1 Introduction

Fabrication of high-performance electron devices on flexible substrates (FS's) is an important challenge for flexible electronics. There are difficulties of deposition of device active layers on FS's, such as strongly limited process temperature and noncrystallinity of ordinary FS's. Although III-V semiconductors as device active layers have excellent electronic properties, such as high electron mobilities and velocities, deposition of high-quality III-V semiconductor thin layers on FS's is problematic due to the difficulties. In fact, an InAs layer of  $\sim 1 \mu\text{m}$  thickness on FS's, which is low-temperature deposited and polycrystalline, exhibits electron mobility of  $\sim 500 \text{ cm}^2/\text{V-s}$  [1]; this mobility, while being higher than those of the polycrystalline Si layers, is far lower than those of crystalline InAs layers. In order to realize high-quality III-V semiconductor thin layers on FS's, bonding method is promising because it does not involve the difficulties of the temperature limitation and the noncrystallinity of FS's. Recently, InP layers of  $\sim 1 \mu\text{m}$  thickness on FS's were formed by bonding method with ion-cut process to separate them from their original substrates, and exhibited electron mobility of  $\sim 900 \text{ cm}^2/\text{V-s}$  [2]. However, the ion-cut process is not simple, while epitaxial lift-off (ELO) process [3, 4] is simple and effective to separate the III-V semiconductor thin layers from their original substrates. In this work, formation of InAs thin layers on FS's was investigated based on our proposal of ELO process of lattice-mismatched-grown narrow-gap III-V semiconductors and van der Waals bonding (VWB) [5]. Establishing 'normal'/'inverted' VWB and etch-thinning methods, we realized InAs thin layers down to  $\sim 100$  nm with very high electron mobilities on FS's.

## 2 Experiments and Results

By means of molecular beam epitaxy (MBE), we grew a heterostructure for ELO-VWB, InAs layer (500 nm) / AlAs sacrificial layer (4 nm) / InAs buffer layer (2500 nm) / GaAs(001) substrate, as well as a structure for reference, InAs (500 nm) / GaAs(001) substrate (Fig. 1). Using the heterostructure, we carried out ELO process, separation of the 500 nm InAs layer by HF selective wet-etching of the sacrificial layer, followed by VWB on a FS, a polyethylene terephthalate (PET) substrate, as shown in Fig. 2. In the 'normal' VWB (NVWB), the InAs layer attached to an adhesive sheet is epitaxial lifted-off and van-der-Waals bonded onto a PET substrate. On the other hand, in the 'inverted' VWB (IVWB), the epitaxial lifted-off InAs layer is firstly transferred to an intermediate support, and then van-der-Waals bonded onto a PET substrate. It

should be noted that the InAs layers obtained by the NVWB and IVWB on PET are oppositely oriented each other. Optimizing both NVWB and IVWB, we obtain so strong bonding of InAs on PET that device fabrication is possible.

By device isolation and non-alloy Ohmic electrode formation, Hall-bar devices were fabricated from the 500 nm InAs layers of the NVWB and IVWB on PET, and also of the reference on GaAs(001). From Hall measurements, we obtain room-temperature electron mobilities and sheet concentrations of  $10700 \text{ cm}^2/\text{V-s}$  and  $1.9 \times 10^{12} \text{ cm}^{-2}$ ,  $10600 \text{ cm}^2/\text{V-s}$  and  $2.0 \times 10^{12} \text{ cm}^{-2}$ , and  $8000 \text{ cm}^2/\text{V-s}$  and  $2.4 \times 10^{12} \text{ cm}^{-2}$ , for the NVWB, the IVWB, and the reference, respectively. This indicates that our ELO-VWB method is effective to realize high-quality InAs thin layers on FS's. Moreover, we carried out etch-thinning of the active regions of these Hall-bar devices as shown in Fig. 3. The etch-thinning without penetration into the InAs/PET interface was realized by  $\text{H}_3\text{PO}_4\text{-H}_2\text{O}_2\text{-H}_2\text{O}$  wet-etchant, owing to optimized bonding. By repeating the etch-thinning and measurements, we obtained electron mobilities and sheet concentrations depending on the thicknesses of the InAs layers, which were checked by a step profiler. Figure 4 summarizes the obtained results. The VWB on PET gives higher electron mobilities than that for the reference, and electron concentrations decreasing with decrease in the thickness, while that for the reference is almost constant probably due to the accumulation layer at the InAs/GaAs interface. The most interesting feature is that the IVWB does not give electron mobilities decreasing with decrease in the thickness, while the NVWB on PET and the reference do; this can be explained by vertical dislocation distributions in lattice-mismatched-grown InAs layers [6]. As a result, InAs on PET obtained by the IVWB exhibits very high electron mobilities  $\gtrsim 10000 \text{ cm}^2/\text{V-s}$  down to  $\sim 100$  nm thickness, which are the highest of those on FS's, and even higher than those of InAs layers on GaAs(111)A and free-standing InAs membranes [7].

## 3 Summary

The formation of InAs thin layers on PET was investigated by ELO and normal/inverted VWB. By the inverted VWB, we realized InAs thin layers down to  $\sim 100$  nm with very high electron mobilities of  $\gtrsim 10000 \text{ cm}^2/\text{V-s}$  on PET, which are the highest of those on flexible substrates.

## References

- [1] M. Takushima, Y. Kajikawa, Y. Kuya, M. Shiba, and K. Ohnishi, Jpn. J. Appl. Phys. **47**, 1469 (2008).
- [2] W. Chen, P. Chen, J. Pulsifer, T. Alford, T. Kuech, and S. Lau, Appl. Phys. Lett. **92**, 212109 (2008).
- [3] M. Konagai, M. Sugimoto, and K. Takahashi, J. Cryst. Growth **45**, 277 (1978).
- [4] E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, Appl. Phys. Lett. **51**, 2222 (1987).
- [5] Y. Jeong, M. Shindo, M. Akabori, and T. Suzuki, Appl. Phys. Express **1**, 021201 (2008).
- [6] Y. Jeong, H. Choi, and T. Suzuki, J. Cryst. Growth **301-302**, 235 (2007).
- [7] H. Yamaguchi, R. Dreyfus, Y. Hirayama, and S. Miyashita, Appl. Phys. Lett. **78**, 2372 (2001).

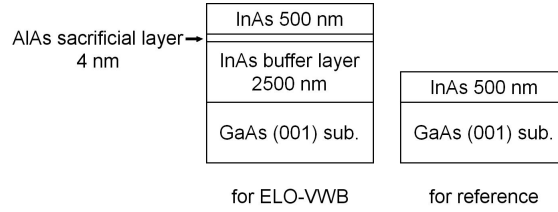


Fig. 1: MBE-grown structures for ELO-VWB and for reference.

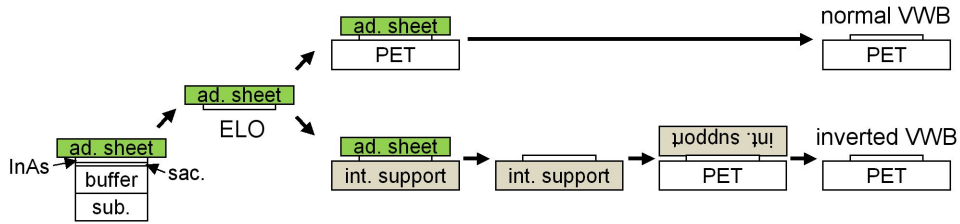


Fig. 2: ELO process and following normal and inverted VWB on PET substrates.

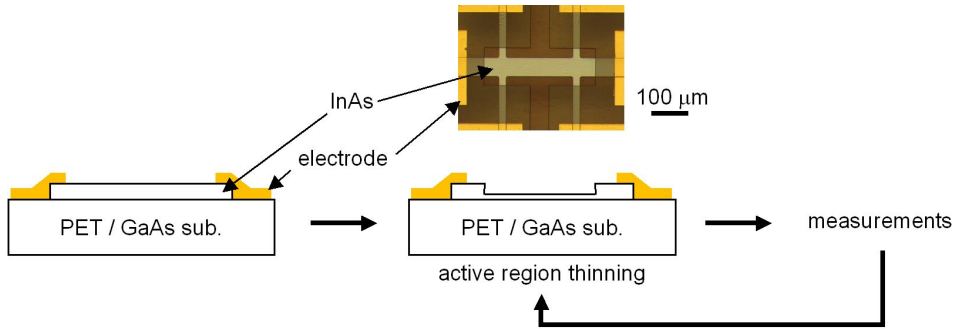


Fig. 3: Etch-thinning of the active regions of InAs Hall-bar devices on PET and GaAs.

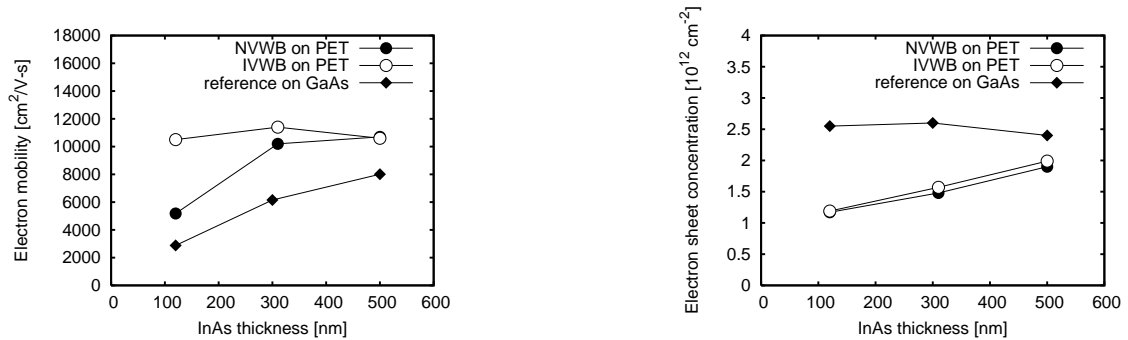


Fig. 4: Electron mobilities (left) and sheet concentrations (right) depending on the InAs layer thicknesses of the active regions of Hall-bar devices on PET and GaAs.