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Fabrication and characterization of InAs/high-k/low-k structures

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Abstract— We fabricated and characterized InAs/high-k/low-k structures, InAs/Al_2O_3/AlN bonded on low-k flexible substrates (FS). Hall-bar devices obtained from the InAs/Al_2O_3/AlN bonded on low-k FS exhibit higher electron sheet concentrations n_s than those obtained from the InAs bonded on low-k FS. In order to elucidate the origin of the higher n_s, we carried out electron energy-loss spectroscopy for the InAs/Al_2O_3 interface. As a result, we found satellite peaks suggesting donor states in Al_2O_3, which can lead to the higher n_s through modulation doping at the InAs/Al_2O_3 interface.

1 Introduction

InAs is a narrow-gap compound semiconductor suitable for applications to mid-infrared optical devices, ultra-high-speed electron devices, and also interband tunnel devices. Heterogeneous integration of InAs thin films on host substrates is important for such device applications. Previously, by using epitaxial lift-off (ELO) and van der Waals bonding (VWB) method [1], we realized InAs/low-k structures [2–5], InAs thin films with high electron mobilities bonded on host low-k flexible substrates (FS), which provide low parasitic capacitances. However, we found serious effects of surface/interface charge scattering and thickness fluctuation scattering on the electron transport properties and low-frequency noise of the InAs/low-k structures [3, 5]. Such electron transport properties can be modified for InAs/high-k/low-k structures, in which thin high-k insulators are employed almost keeping low parasitic capacitances of the low-k substrates. In this work, we fabricated and characterized InAs/Al_2O_3/AlN bonded on low-k FS; the electron transport properties are compared to those of the InAs bonded on low-k FS. In relation with the electron transport properties, electron energy-loss spectroscopy (EELS) results for the InAs/Al_2O_3 interface are discussed.

2 Fabrication of InAs/Al_2O_3/AlN bonded on low-k flexible substrates

We fabricated InAs/Al_2O_3/AlN bonded on low-k FS (InAs/Al_2O_3/AlN/FS) as follows. Using a heterostructure, InAs device layer/sacrificial layer/InAs buffer layer/GaAs(001), we carried out ELO, separation of the InAs device layer attached to an adhesive sheet, followed by bonding onto an intermediate support (IS), a sapphire(0001) coated by resists. After removal of the adhesive sheet, a high-k insulator deposition was carried out on the InAs/IS to obtain AlN/Al_2O_3/InAs/IS; Al_2O_3 ($\sim$ 50 nm thickness) and AlN ($\sim$ 30 nm thickness) were formed by atomic layer deposition using trimethylaluminum-H_2O and by sputtering deposition using an AlN target, respectively. The AlN/Al_2O_3/InAs was separated from the IS, followed by "inverted" VWB on low-k FS [2, 3, 5]; we obtained InAs/Al_2O_3/AlN/FS. The choice of the AlN/Al_2O_3 as a high-k insulator is helpful for easiness of the VWB. From the InAs/Al_2O_3/AlN/FS, Hall-bar devices were obtained as shown in Fig. 1(a), by isolation, Ohmic electrode formation, and channel thinning by wet etching. Several InAs channel thicknesses $d \simeq$ 10-100 nm are obtained, where the "inverted" VWB is advantageous to obtain a high crystal quality after the thinning according to the growth-direction dislocation distribution [6]. From the heterostructure, we also fabricated InAs bonded on low-k FS (InAs/FS) and Hall-bar devices shown in Fig. 1(b), using the "inverted" VWB without the high-k insulator deposition.

3 Characterization of InAs/Al_2O_3/AlN bonded on low-k flexible substrates

From room-temperature measurements of the InAs/Al_2O_3/AlN/FS and the InAs/FS Hall-bar devices, we obtained electron sheet concentrations n_s as well as electron mobilities μ. Figure 2 shows n_s as functions of InAs thickness d, with the inset showing μ as functions of d. We find that InAs/Al_2O_3/AlN/FS exhibits higher n_s with a smaller dispersion than InAs/FS. We also find that InAs/Al_2O_3/AlN/FS exhibits similar but slightly lower μ than InAs/FS. This suggests scattering centers existing near the InAs/Al_2O_3 interface.

In order to elucidate the origin of the above results, we carried out EELS for the InAs/Al_2O_3 interface using a scanning transmission electron microscope (STEM) with an acceleration voltage of 120 kV. Figure 3 shows a high angle annular dark field (HAADF) STEM image of the InAs/Al_2O_3 interface, where the origin of the position x is determined by the O1s edge peak height shown below. Figure 4 shows examples of EELS spectra for the position $x = -2$-$+3$ nm. While clear O1s edge peaks near 539 eV are observed for $x \gtrsim 0$ nm, clear satellite peaks at 532 eV are observed for $x \gtrsim 1$ nm. Figure 5 shows O1s edge peak and satellite peak heights as functions of x, which are fitted by $\propto [1 + \mathrm{erf}[(x - x_0)/\sqrt{2}\sigma]]/2$ using the error function. We obtain $x_0 = 0$ nm (the definition of the origin) and $\sigma \simeq 1.6$ nm for the O1s edge peak, while $x_0 \simeq 1.4$ nm and $\sigma \simeq 0.35$ nm for the satellite peak. The satellite peak height increases for 1 nm $\lesssim x \lesssim$ 2 nm, becoming almost constant for $x \gtrsim 2$ nm. It has been reported that, electrons occupying oxygen-vacancy donor states in Al_2O_3 can be the origin of the satellite peak, while unoccupied oxygen-vacancy donors (ionized donors) do not give the satellite peak [7].

Therefore, we consider that oxygen-vacancy donors are ionized near the InAs/Al_2O_3 interface, while not ionized for the Al_2O_3-inside. This suggests that modulation doping takes place at the InAs/Al_2O_3 interface leading to the higher n_s; the oxygen-vacancy donors near the interface provide electrons in the InAs channel, and become ionized donors and scattering centers.

4 Summary

We fabricated and characterized InAs/Al_2O_3/AlN/FS, which exhibits higher n_s than InAs/FS. EELS results indicate that modulation doping takes place at the InAs/Al_2O_3 interface leading to the higher n_s.

Acknowledgment

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References

[1] Y. Jeong, M. Shindo, M. Akabori, and T. Suzuki, Appl. Phys. Express **1**, 021201 (2008).

[2] H. Takita, N. Hashimoto, C. T. Nguyen, M. Kudo, M. Akabori, and T. Suzuki, Appl. Phys. Lett. **97**, 012102 (2010).

[3] C. T. Nguyen, H.-A. Shih, M. Akabori, and T. Suzuki, Appl. Phys. Lett. **100**, 232103 (2012).

[4] T. Suzuki, H. Takita, C. T. Nguyen, and K. Iiyama, AIP Advances **2**, 042105 (2012).

[5] S. P. Le, T. Ui, and T. Suzuki, Appl. Phys. Lett. **107**, 192103 (2015).

[6] Y. Jeong, H. Choi, and T. Suzuki, J. Cryst. Growth **301-302**, 235 (2007).

[7] S. Nigo, M. Kubota, Y. Harada, T. Hirayama, S. Kato, H. Kitazawa, and G. Kido, J. Appl. Phys. **112**, 033711 (2012).

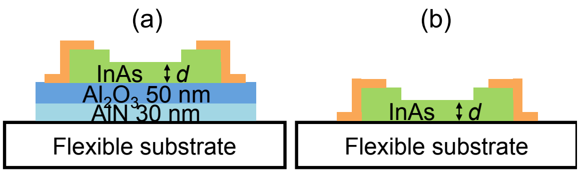

Fig. 1: Schematics of Hall-bar devices obtained from (a) InAs/Al_2O_3/AlN/FS and (b) InAs/FS.

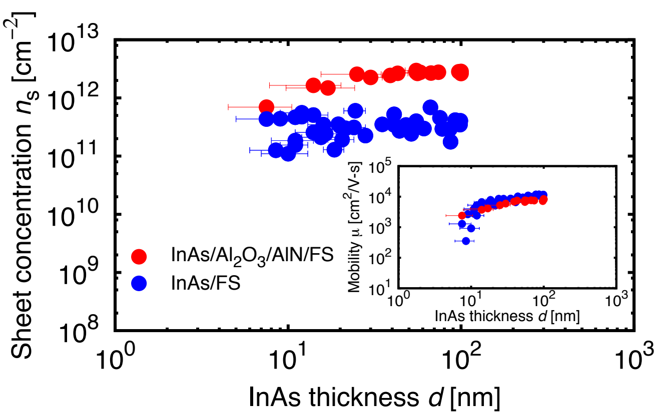

Fig. 2: Electron sheet concentrations n_s and mobilities μ as functions of InAs thickness d.

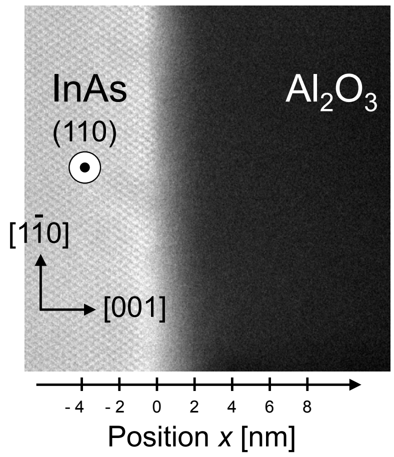

Fig. 3: A HAADF STEM image of the InAs/Al_2O_3 interface.

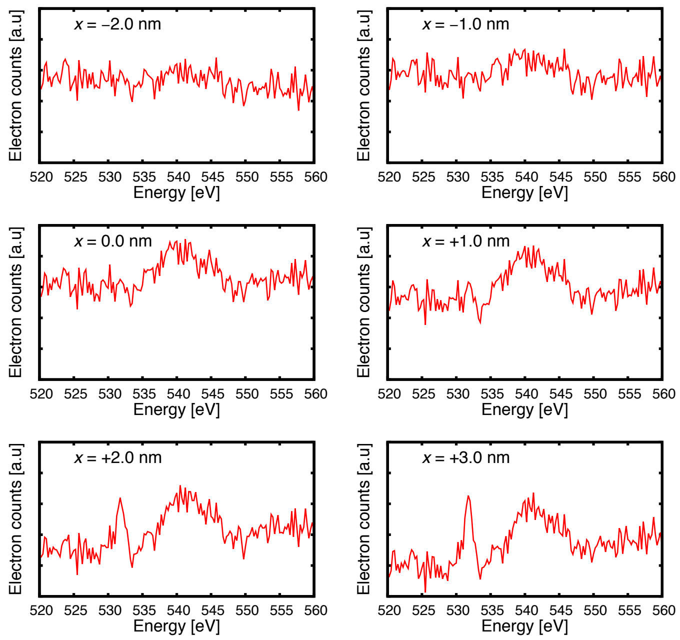

Fig. 4: EELS spectra for the position $x = -2$–$+3$ nm.

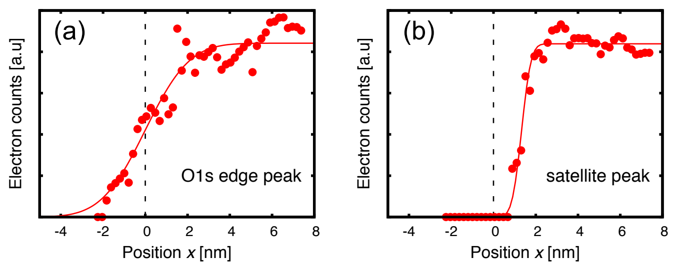

Fig. 5: (a) O1s edge peak and (b) satellite peak heights as functions of the position x.