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Electron Transport of Low Transmission Barrier between Ferromagnet and Two-Dimensional Electron Gas (2DEG)

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The junction properties between the ferromagnet (FM) and two-dimensional electron gas (2DEG) system are crucial to develop spin electronic devices. Two types of 2DEG layer, InAs and GaAs channel heterostructures, are fabricated to compare the junction properties of the two systems. InAs-based 2DEG layer with low transmission barrier contacts FM and shows ohmic behavior. GaAs-based 2DEG layer with Al_2O_3 tunneling layer is also prepared. During heat treatment at the furnace, arsenic gas was evaporated and top AlAs layer was converted to aluminum oxide layer. This new method of forming spin injection barrier on 2DEG system is very efficient to obtain tunneling behavior. In the potentiometric measurement, spin-orbit coupling of 2DEG layer is observed in the interface between FM and InAs channel 2DEG layers, which proves the efficient junction property of spin injection barrier.

Key words : 2DEG, GaAs, InAs, ohmic, schottky, potentiometric measurement

1. Introduction

Spin field effect transistor (spin-FET) is mainly considered in the field of spin electronics because of its potential performance for the electronic device. Previous researches show that the injected spins transferred from ferromagnet (FM) to metal or semiconductor within the spin flip length [1]. Jedema *et al.* also demonstrated that spin injection and accumulation in all metal system and metal-insulator-metal system [2, 3]. However, spin transport in two-dimensional electron gas (2DEG) with high electron mobility is essential for realizing spin transport devices [1, 4]. From the earlier results, we believe that a low transmission barrier is a major factor for the efficient spin injection [1]. Therefore the electrical property of ferromatgnet-2DEG junction in addition to design of 2DEG layer is crucial point of spin electronics.

In this paper, two different 2DEG systems that are InAs and GaAs channel based high electron mobility transistor (HEMT) structures are presented. In the InAs channel system a semiconductor based low transmission barrier is adopted while an AlAs converted Al_2O_3 is used for the low transmission barrier in the GaAs channel system. A novel type of oxidation process in the spin injection barrier is used for the GaAs channel structure. Ferromagnet is deposited on the top of the 2DEG structure and the junction properties including detection of spin-orbit coupling were investigated in this study.

2. Experimental

The cross-sectional view of InAs channel HEMT structure is shown in Fig. 1. InAs channel layer is

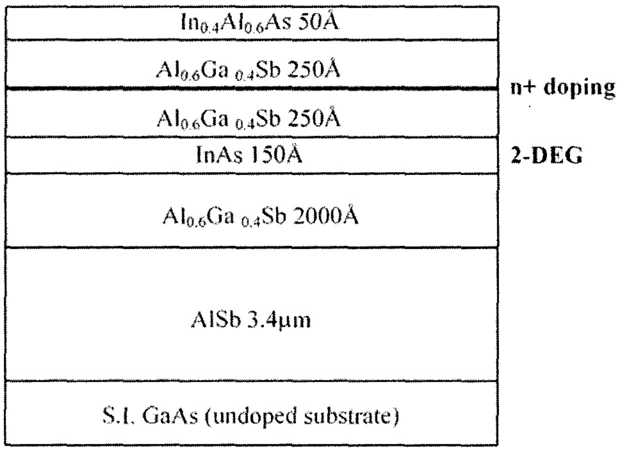

Fig. 1. Cross-sectional view of InAs channel HEMT structure.

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*Corresponding author: Tel: +82-2-958-5423, Fax: +82-2-958-6851, e-mail: hckoo@kist.re.kr sandwiched with $Al_{0.6}Ga_{0.4}Sb$ cladding layers. Arsenic doping is inserted in the top cladding layer. $In_{0.4}Al_{0.6}As$ capping layer is grown on the top of the $Al_{0.6}Ga_{0.4}Sb$ layer and this capping plays a role of blocking the hole leakage and protects the cladding layer during further process. AlSb buffer layer on the semi-insulating GaAs substrate is grown for releasing lattice mismatch. The electron mobility of the InAs 2DEG wafer at 300 K (15 K) is19430 $cm^2/V{\cdot}s$ (66670 $cm^2/V{\cdot}s$).

Fig. 2. shows the cross-section of GaAs channel HEMT structure. In this case 2DEG channel is formed between the intrinsic $Al_{0.3}Ga_{0.7}As$ and GaAs. Supper-lattice layers of $GaAs/Al_{0.5}Ga_{0.5}As$ are grown in order to reduce stress due to the lattice mismatch. A carrier supply layer is located just below the GaAs capping layer. The electron mobility of this system is 1984 m^2/Vs (23837 cm^2/Vs) at 300 K (77 K). Native oxides of $Al_xGa_{1-x}As$ have attracted attentions as an insulating layer of various semiconductor devices because of their reproducibility and uniformity. The formation of $Al_xGa_{1-x}As$ is possible using modern growth technology without breaking the vacuum. Therefore, many semiconductor devices have been demonstrated with these oxides [5]. Especially, Al_2O_3 transformed from $Al_{0.98}Ga_{0.02}As$ and AlAs is promising due to its superior structural and electronic properties [6]. In this experiment, we utilize an accelerating process for growing Al_2O_3 layer on the top of two dimensional electron gas layers as shown in Fig. 2. Fig. 3(a) shows the schematic diagram of oxidation process. Firstly, AlAs layer was grown as soon as GaAs capping layer was deposited without breaking the vacuum of molecular beam epitaxy (MBE) chamber. After growth, AlAs layer was oxidized in an open tube furnace, where water vapor was introduced with N_2 carrier gas by 100 cc/min. The sample was kept at 460 °C during 12 hours in the furnace to oxidize the AlAs layer around the entire sample. Arsenic was combined with hydrogen and evaporated in the form of AsH_3. Finally an Al_2O_3 layer is formed on the top of the substrate. The thickness of the resulting Al_2O_3 is reduced by 7.5% from initial height of AlAs layer and therefore we can control the oxide thickness easily. Fig. 3(b) shows the topography of Al_2O_3 surface that was made by new method described above and the image was obtained by atomic force microscopy. As shown in the image, the grain is regularly packed and the size is 30-40 nm. The bright and dark parts indicate high and low thickness, respectively, but the RMS roughness is only 1.52 Å. Since the RMS roughness of GaAs layer is also 1.5 Å, it is confirmed that the oxide is evenly formed. The final step is ferromagnet deposition in order to investigate junction properties. The patterning of $Co_{0.9}Fe_{0.1}$ is performed by electron lithography and the film thickness is 600 Å.

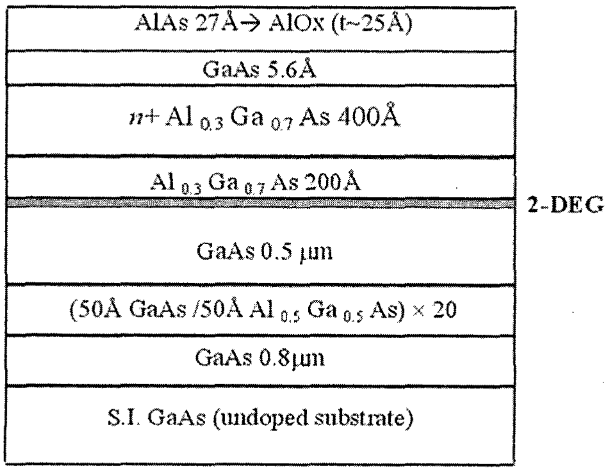

Fig. 2. Cross-sectional view of GaAs channel HEMT structure.

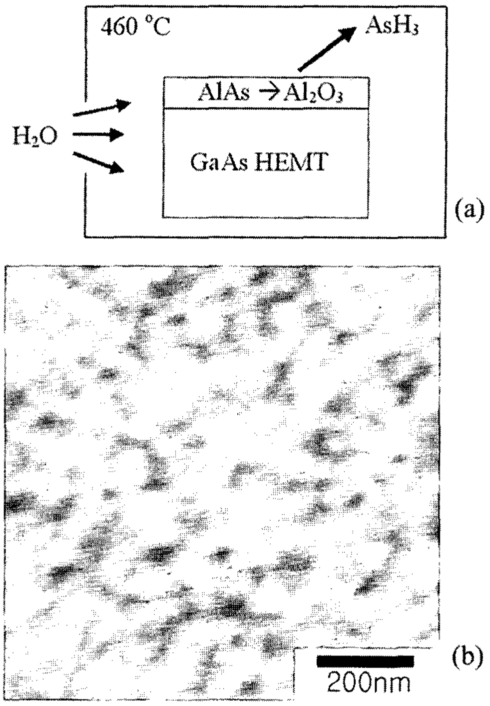

Fig. 3. (a) Experiment diagram of oxidation process from AlAs to Al_2O_3. Al is combined with oxygen and As is evaporated with hydrogen. (b) Atomic force microscopy image of Al_2O_3 surface. The RMS roughness is 1.52 Å and the grain size is 30-40 nm.

3. Results and Discussion

Fig. 4 shows the schematic energy band diagram of two types of wafers including ferromagnet. As shown in Fig.

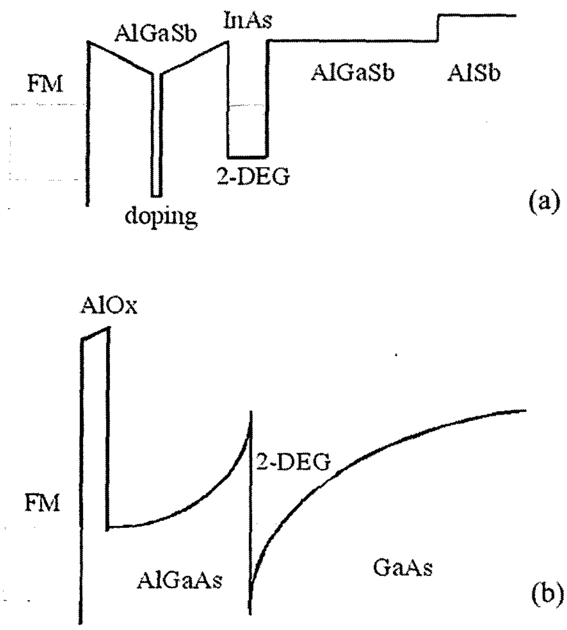

Fig. 4. Schematic energy band diagram of (a) InAs and (b) GaAs channel HEMT.

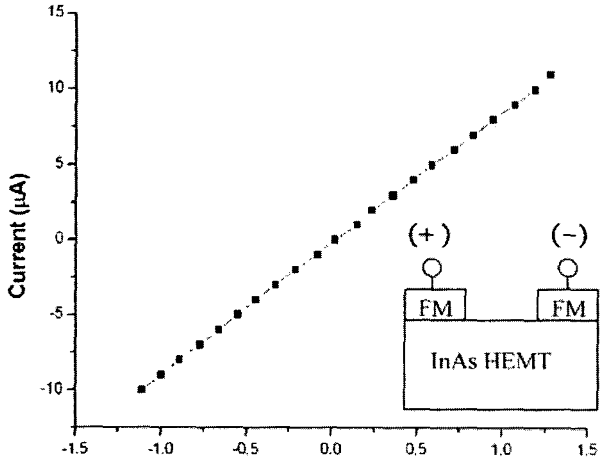

Fig. 5. Current-voltage characteristic of InAs channel with two ferromagnetic electrodes.

4(a), InAs active layer is formed between AlGaSb claddings and the doping layer supplies the carriers to the quantum well. Usually the junction between InAs and metal forms ohmic contact. Fig. 5 shows current-voltage characteristic curves of ferromagnet/2DEG junction. The linear curve indicates that ohmic contact is well established even at low voltage. The contact resistance is calculated by TLM (Transmission line method) measurement and the RA value is 1-5 × 10^5 Ω-μm^2.

Fig. 4(b) shows the energy barrier of GaAs channel HEMT structure. Inversion layer is created between the AlGaAs and GaAs interface. The tunneling barrier

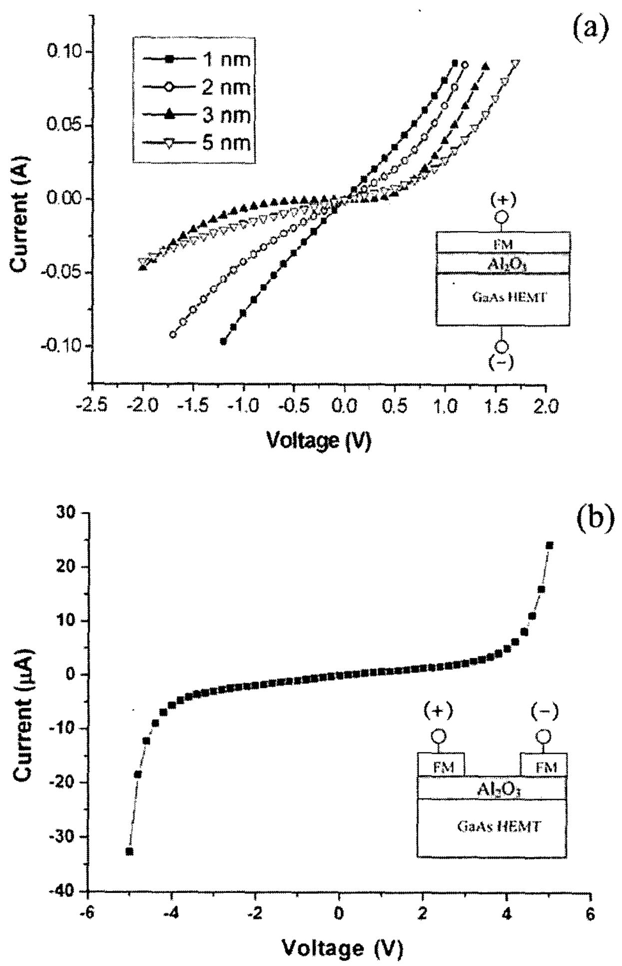

Fig. 6. Current-voltage characteristic of (a) ferromagnet-oxide-GaAs junction as a function of oxide thickness and (b) GaAs channel with two ferromagnetic electrodes.

created by new method is formed on the top of wafers. In order to verify the tunneling characteristic, $Co_{0.84}Fe_{0.16}$ was deposited on the substrate. While the voltage is applied between the two ferromagnetic electrodes, the current is measured on the same electrodes. The current path is from ferromanet to 2DEG through oxide barrier. The electron flows into the perpendicular direction to the channel as shown in geometry diagram of Fig. 6(a). Generally CoFe-GaAs contact forms schottky barrier, but this results indicate conventional tunneling behavior. Spin-LED can utilize schottky barrier because the injected spin is detected in bulk-like recombination region without any electrical transfer from semiconductor to ferromagnet. However, the detection part has to be considered in the electrical transport. In schottky barrier system, the reversed injector always has the forward biased detector, which would reduce the detectin efficiency. Fig. 6(a) shows the I-V curves of ferrmagnet-semiconductor tunneling junctions as a function of the oxide thickness. For the electrical contact of the bottom, the heavily doped substrate is used in this experiment. The curve shows same shape for the both direction of the current, and therefore it is believed to be not the schottky barrier but the tunneling junction. However, for the 1 nm thick film it looks like just low-voltage schottky behavior and the reason is that 1 nm is not enough to block the leakage current.

Fig. 6(b) shows current-voltage characteristics of ferromagnet-oxide–semiconductor–oxide-ferromagnet structure. Inset diagram indicates the measurement geometry and it shows that the electrons experience tunneling barrier twice. When the applied voltage is less than 4 V, the electron cannot flow into the semiconductor due to the tunneling barrier. Above critical voltage, the tunneling current suddenly increases. Therefore, the I-V curves clarify that Al_2O_3 layer was well formed without leakage current. The size of the ferromagnetic electrode is 100 mm by 200 mm and the contact resistance is 79 kΩ for I = 20 mA. It is assumed that all current flows through the two-dimensional electron gas layer. This large contact resistance could be the obstacle for low power devices, so further surface treatment is necessary. Electrical transport in GaAs channel is quite different because the ohmic contact is very difficult and the mobility is relatively low compared to InAs based channel [7]. In spite of these demerits, GaAs channel has an advantage of small spin-orbit field which can help the injected spin to propagate without losing spin information.

Fig. 7 shows a so-called potentiometric measurement at the junction between InAs 2DEG and FM. The bias current was applied into 2DEG layers and the voltage was measured from the FM to the end of 2DEG layer. Only 2DEG layer in the shaded region was remained and the other area was milled out. Spin-orbit coupling of the FM-2DEG junction can arise from an asymmetry in the confining quantum well and an electric field normal to the 2DEG plane (E_z) is produced [4, 8]. The high mobility electrons traveling to the x direction in 2DEG feel the electric field (E_z) and an effective magnetic field (H_y). This magnetic field shifts the spin sub-band of up and down spins in 2DEG and this shift results in a net magnetization in 2DEG whose direction depends on the direction of the bias current. In the potentiometric geometry, the spin subband difference of chemical potential in the 2DEG is measured by changing the magnetization direction of FM. This measurement gives a hysteresis loop-like potential curve. The measured R_p values in the potentiometric geometry at 5 K are presented in Fig. 7. The size of $Co_{0.9}Fe_{0.1}$ pattern is 2.4 μm wide and 17 μm long. The potential difference ΔV at 5 K is about 0.17 mV ($= I \times \Delta R = 50\ \mu\text{A} \times 3.4\ \Omega$) and this value is nearly unchanged at 77 K. The spin-orbit coupling makes it possible to modulate spin information inside channel, so 2DEG is essential to develop spin field effect transistor. GaAs channel has very small spin-orbit coupling field, so that the signal of potentiometric measurement is too weak to be sensed.

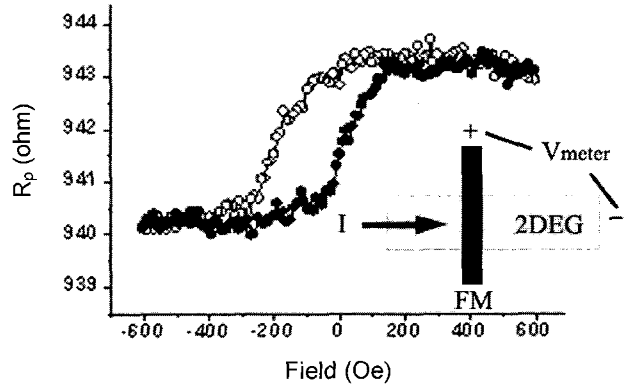

Fig. 7. Potentiometric measurement of InAs channel HEMT at $T = 4$ K.

4. Conclusions

The transport properties of 2DEG-FM junction are very important factor to realize spin electronic devices. We fabricated AlGaSb/InAs/AlGaSb HEMT structure and shows ohmic behavior with FM patterns. The other design is GaAs based HEMT structure with Al_2O_3 layer that is the tunneling barrier between the FM to 2DEG by using a new type of oxidation process. The RMS value of oxidation layer is 1.52 Å and the junction shows tunneling behavior which is effective for spin injection. In the potentiometric measurement, spin-orbit coupling of 2DEG layer is displayed in the interface between FM and InAs channel 2DEG layers.

Acknowledgment

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