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Spin-orbit interactions in InGaAs/InAlAs inverted HEMTs for Rashba spintronics devices

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Rashba spin-field effect transistor (FET) is one attractive issue in new devices physics and in semiconduct or spintronics applications. So far, numerous progresses have been made toward Rashba spin-FET operations such as the strong and gate-controllable spin-orbit (SO) interaction in various narrow-gap heterojunctions and the long spin coherence length ensured by high electron mobility [1]. However, highly effective spin injection/detection of spin-polarized carriers from the ferromagnetic (FM) source into a two-dimensional electron gas (2DEG) is still not solved at present. We here focused on the narrow-gap InGaAs/InAlAs inverted (i-)HEMT as a candidate structure to reveal a high spin-injection efficiency, since the material h as a thin and low barrier InGaAs surface channel with still keeping a high 2DEG mobility as well as a lar ge SO coupling constant

We have grown inverted $In_xGa_{1-x}As/In_xAl_{1-x}As$ x=0.5 (and 0.75) modulation-doped i-HEMT structures with 60 nm and 30 (40) nm channel thickness (d_c) by molecular beam epitaxy via metamorphic step graded buffer layer on semi-insulating GaAs (100) substrate. And also a normal InGaAs/InAlAs structure was grown for a reference. For basic spin transport analysis, regular Van der Pauw (size=5×5 mm^2) and Hall bar samples (channel length of 50 μm and width of 200 μm with different channel directions [1-10], [110] and [100]) were prepared by photolithography. The SO coupling constant, α, is deduced by the fast Fourier transformation (FFT) and beating nodes Landau plot of the oscillations observed in the low field Shubnikov-de Haas (SdH) signals at ~1.5 K. We then fabricated various (side- and top-electrode types) FM ($Ni_{50}Fe_{50}$) /2DEG/FM two-terminal samples on the surface of the above i-HEMTs and carried out usual spin-valve (S V) measurements at 1.5 K. Main results obtained in this work are as follows:

1) The 50 and 75 % In-content i-HEMT samples with surface InGaAs channel thickness down to d_c ~30 nm have thus been grown by molecular beam epitaxy on GaAs(001) substrates via InAlAs step graded buffer. Low temperature electron mobility of the 2DEG to 5 and 20×10^4 cm^2/Vsec was obtained for the typical sheet electron density of ~10^{-12} /cm^2 for In-content of 50 and 75 %, respectively. Those values are enough to half spin precession length for spin-transistor devices.

2) The Rashba SO interaction has been estimated from analysis of the low field Shubnikov-de Haas (SdH) oscillation and weak anti-localization fitting in the 2DEG. In both cases of 50 and 75 % contents, the large SO coupling constants, $\alpha >$ ~10×10^{-12} eVm, comparable to those of the normal-HEMT were confirmed. Moreover, larger αs were found in the 75 % HEMTs than those in the 50 % ones. This is due to the differences in the energy band-gap, the electron effective mass, and the interface mean electric field strength between the 75 % and 50 % samples, respectively.

3) In addition, also larger α was found for the thinner InGaAs channel samples in the same In-content: αs were ~16 and ~20×10^{-12} eVm for 75 % the d_c =60 and 40 nm samples, respectively. The origin of this larger α is probably due to the stronger interface electric field resulting from the thinner triangular potential well at the 2DEG interface. Those α values correspond as high as ~8 meV spin-splitting at the Fermi level.

4) The reproducible SV signals have observed in both the electrode type samples. The resistance variation ratio, $\Delta R/R_0$, in the top type reaches up to ~1 %, while that in the side type remains as high as 0.2 %. This difference, however, cannot be attributed to the type difference of the electrode (top or side), since the electrode spacing (D) and width are different between the two samples. The value, $\Delta R/R_0$ ~ 1 %, in the top type sample is one of the highest ones obtained in this type of experiments and could be higher than those in our previous normal HEMT sample. But it is not yet concluded that this is mainly due to the adoption of the i-HEMTs proposed here, since the contact resistances are still much larger than those of the 2DEG channels and not reproducible among the samples with similar dimensions. So that, the electronic nature of the electrodes (ohmic or tunnel) are still not entirely designed and identified. We observed, however, the dependency of the SV signal on D, the electrode spacing. The D values were nominally 1.0, 1.5 and 2.0 μm and they are all less than the mean free path of the 2DEG. So that, the three samples measured here are divided into the so-called ballistic regime. If this was the case, the value, $\Delta R/R_0$, would be invariant against D. But, we observed here the decrease of $\Delta R/R_0$ (from 0.15 to 0.05 %) with increase of D from 1.0 to 2.0 μm. This may suggests that the 2DEG mobility possibly degraded in the device fabrication process would restrict the spin coherence length within the same order.

It is thus concluded that the i-HEMTs developed and estimated in this work are worthy as basic research to make a variety of Rashba devices for spintronics or spin transport physics.