Extended Abstracts of the 1998 International Conference on Solid State Devices and Materials, Hiroshima, 1998, pp. 400–401

From Strain-Compensated $In_{0.80}Ga_{0.20}As$/InAlAs to InAs/InAlAs HEMT's

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1.Introduction

It is shown both theoretically and experimentally that the performance of $In_{0.53+x}Ga_{0.47-x}As$ pseudomorphic HEMT's can be further improved by increasing In composition. Therefore record high f_T and f_T-L_g product of 340 GHz [1] and 57 GHz-µm [2] have been achieved in $In_{0.8}Ga_{0.2}As$ channel and $In_{0.77}Ga_{0.23}As/In_{0.25}Ga_{0.75}As$ strain-compensated channel, respectively. The main reasons of such performance improvement are due to the lower electron effective mass, higher electron mobility and peak velocity, and better carrier confinement in the $In_{0.53+x}Ga_{0.47-x}As$ quantum well. Further performance improvement can be expected by increasing In-composition to InAs, but the primary challenge is to avoid the large strain-induced island growth and rough interface. Moreover, the large strain from InAs and InP lattice-mismatch is beyond the capability of our previous reported strain-compensated design [3]-[4], even though we have successfully demonstrated very high electron mobility and device performance using $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As/In_{0.52}Al_{0.48}As$ strain-compensated heterostructure. In this work, we have used a new buffer layer to reduce the large strain and transfer the lattice constant from $In_{0.52}Al_{0.48}As$ to $In_{0.75}Al_{0.25}As$. Therefore, $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ strain-compensated HEMT can be successfully fabricated on this buffer layer. Room-temperature mobility of 20,200 cm^2/Vs is measured, with a carrier concentration of $2.7x10^{12}$ cm^{-2}. The merit of the InAs channel design is further confirmed by the good f_T of 51-GHz in a 1.1-µm device. To the best of our knowledge, this is the highest f_T for 1-µm transistors.

2.Experimental

All wafers were grown in a MBE system. The layer structure of InAs channel HEMT consists of a 200-nm $In_{0.52}Al_{0.48}As$ lattice-matched layer to InP, a 200-nm $In_xAl_{1-x}As$ buffer, an active channel, a 4-nm $In_{0.52}Al_{0.48}As$ spacer, a 4-nm n^+-$In_{0.52}Al_{0.48}As$ donor layer, a 20-nm $In_{0.52}Al_{0.48}As$ Schottky layer, and a 4-nm n^+-$In_{0.75}Ga_{0.25}As$ ohmic contact layer. The active channel contains a 7-nm InAs layer, with two 1.5-nm $In_{0.75}Ga_{0.25}As$ interface smooth layers. As mentioned above, the key factor to form InAs HEMT is to release part of strain in the $In_xAl_{1-x}As$ buffer, and the rest of the strain can be balanced using the strain-compensated heterostructure. It is therefore very important to successfully design and grow such buffer layer. We have designed several different buffer layers to transfer the lattice constant from $In_{0.52}Al_{0.48}As$ to $In_{0.75}Al_{0.25}As$; these include a uniform $In_{0.75}Al_{0.25}As$, a linearly graded $In_xAl_{1-x}As$ (x from 0.52 to 0.75), and a step-graded $In_{0.59}Al_{0.41}As/In_{0.67}Al_{0.33}As/In_{0.75}Al_{0.25}As$. However, none of these structures can give good performance. Improved electron mobility can only be obtained using the multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattice buffer.

3.Results and Discussion

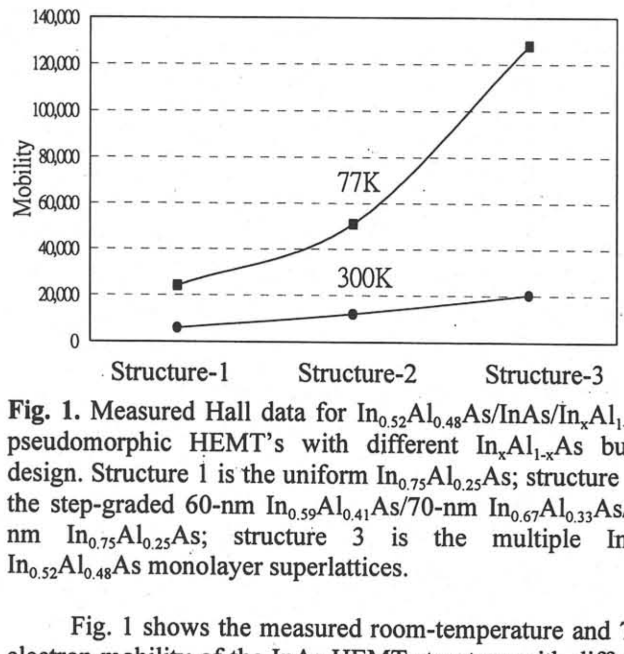

Fig. 1. Measured Hall data for $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT's with different $In_xAl_{1-x}As$ buffer design. Structure 1 is the uniform $In_{0.75}Al_{0.25}As$; structure 2 is the step-graded 60-nm $In_{0.59}Al_{0.41}As$/70-nm $In_{0.67}Al_{0.33}As$/70-nm $In_{0.75}Al_{0.25}As$; structure 3 is the multiple InAs/$In_{0.52}Al_{0.48}As$ monolayer superlattices.

Fig. 1 shows the measured room-temperature and 77K electron mobility of the InAs HEMT structure with different buffer layer design. For comparison, the electron-mobilities from strain-compensated $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As/In_{0.52}Al_{0.48}As$ HEMT, without strain relaxation buffer, are 15,000 and 123,000 cm^2/Vs at room-temperature and 77K, respectively. Therefore the conventional uniform and step-graded buffer layer design not only have no improvement but also degrade the performance, even though only 23% increase of In composition. In sharp contrast with the same amount In composition on GaAs, $In_{0.23}Ga_{0.77}As$ strain-relaxed buffer grown on GaAs shows much improved performance. The above difference is due to the formation of 3-dimentional island growth at high In composition. Therefore we have used the monolayer superlattice to increase the migration length and suppress the island growth. Although using such buffer layer increases room-temperature mobility, the 77K mobility shows little improvement to strain-compensated $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As/In_{0.52}Al_{0.48}As$ HEMT. Therefore residual defects may still exist even using this buffer design.

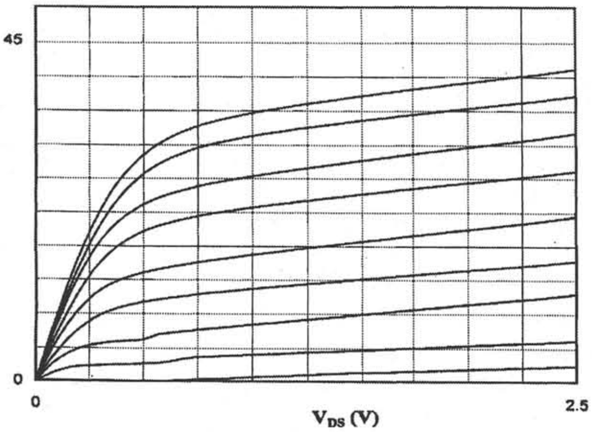

Fig. 2. I-V characteristics of a typical 1.1-μm $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT with multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices buffer (V_{GS}=-0.2 V/step, 0.4 V top curve).

We have therefore fabricated transistor on this strain-compensated $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ structure using monolayer superlattice buffer. Fig. 2 shows the DC transistor I-V characteristic. A peak g_m of 714 mS/mm is obtained with only small kinks at low currents. This is an indication that the transistor has good DC characteristic and suitable for further RF measurement.

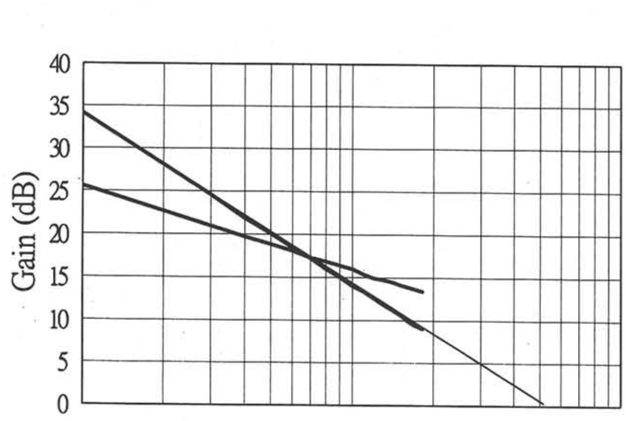

Fig. 3. Gain versus frequency for a typical 1.1-μm $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT with multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices buffer.

The microwave characterization was performed using a CASCADE on-wafer probe and network analyzer. Fig. 3 shows the calculated H_{21} and MSG from measured S-parameter data. An extrapolated f_T of 51-GHz is obtained from the 1.1-μm gate-length transistor, which demonstrate the excellent RF performance of device. The extrapolated f_{max} is more than 100-GHz from equivalent circuit model.

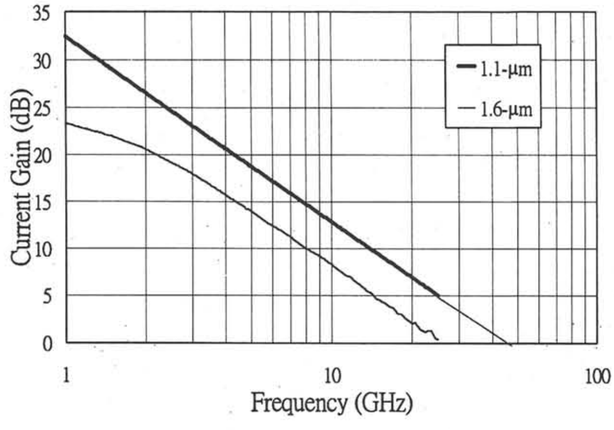

Fig. 4. Gain versus frequency for 1.1-μm and 1.6-μm $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As$ pseudomorphic HEMT's.

For comparison purpose, we have also fabricated the transistor with strain-compensated $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As/In_{0.52}Al_{0.48}As$ structure. As shown in Fig. 4, a extrapolated f_T of 45-GHz is obtained for the same gate length. It is not surprising that the HEMT fabricated using InAs channel have superior f_T, which is primary dominated by the smaller electron effective mass in InAs than that of $In_{0.80}Ga_{0.420}As$ channel.

4.Conclusion

In conclusion, we have developed a strain-compensated $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT. The success of this work is based on the good strain-relaxation buffer layer and suppression of 3-dimentional island growth, using multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices buffer. The success of this design can be further demonstrated from the very high room temperature mobility of 20,200 cm^2/Vs at a high carrier density of $2.7x10^{12}$ cm^{-2}, and f_T of 51-GHz in a 1.1-μm transistor.

Acknowledgments

We would like to express sincere thanks to Dept. Head-Prof. T. F. Lei for his continuous support.

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