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$_{0.33}$Ga$_{0.67}$As pseudomorphic HEMT's can be further improved by increasing In composition. Therefore record high $f_T$ and $f_{-3dB}$ product of 340 GHz [1] and 57 GHz-\mu$m$ [2] have been achieved in In$_x$Ga$_{1-x}$As channel and In$_{0.33}$Ga$_{0.67}$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$_{0.51}$Ga$_{0.49}$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$_{0.6}$Ga$_{0.4}$As/In$_{0.33}$Ga$_{0.67}$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$_{0.35}$Al$_{0.65}$As. Therefore, In$_{0.52}$Al$_{0.48}$As/InAs/In$_{0.57}$Al$_{0.43}$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 2.75x10$^12$ cm$^{-2}$. The merit of the InAs channel design is further confirmed by the good $f_T$ of 51-GHz in a 1.1-\mu$m$ device. To the best of our knowledge, this is the highest $f_T$ for 1-\mu$m$ transistors.

2. Experimental

All wafers were grown in a MBE system. The lattice structure of InAs channel HEMT consists of a 200-nm In$_{0.35}$Al$_{0.65}$As lattice-matched layer to InP, a 200-nm In$_{0.57}$Al$_{0.43}$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$_{0.35}$Ga$_{0.65}$As interface smooth layers. As mentioned above, the key factor to form InAs HEMT is to release part of strain in the In$_{0.57}$Al$_{0.43}$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$_{0.5}$Al$_{0.5}$As (x from 0.52 to 0.75), and a step-graded In$_{0.35}$Al$_{0.41}$As/In$_{0.45}$Al$_{0.55}$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$_{0.35}$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$_{0.57}$Al$_{0.43}$As pseudomorphic HEMT's with different In$_{0.57}$Al$_{0.43}$As buffer design. Structure 1 is the uniform In$_{0.75}$Al$_{0.25}$As; structure 2 is the step-graded 60-nm In$_{0.35}$Al$_{0.41}$As/70-nm In$_{0.45}$Al$_{0.55}$As/70-nm In$_{0.75}$Al$_{0.25}$As; structure 3 is the multiple InAs/In$_{0.35}$Al$_{0.48}$As monolayer superlattices.](image)

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$_{0.6}$Ga$_{0.4}$As/In$_{0.33}$Ga$_{0.67}$As/In$_{0.35}$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$_{0.33}$Ga$_{0.67}$As strain-relaxed buffer grown on GaAs shows much improved performance. The above difference is due to the formation of 3-dimensional 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$_{0.52}$Ga$_{0.48}$As/In$_{0.52}$Ga$_{0.48}$As pseudomorphic HEMT. Therefore residual defects may still exist even using this buffer design.

![Graph](image1)

Fig. 2. I-V characteristics of a typical 1.1-μm In$_{0.52}$Al$_{0.48}$As/InAs buffer 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$_{0.52}$Al$_{0.48}$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.

![Graph](image2)

Fig. 3. Gain versus frequency for a typical 1.1-μm In$_{0.52}$Al$_{0.48}$As/InAs/In$_{0.52}$Al$_{0.48}$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$_2$ and MSG from measured S-parameter data. An extrapolated f$_g$ 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.

![Graph](image3)

Fig. 4. Gain versus frequency for 1.1-μm and 1.6-μm In$_{0.4}$Ga$_{0.6}$As/In$_{0.4}$Ga$_{0.6}$As pseudomorphic HEMT's.

For comparison purpose, we have also fabricated the transistor with strain-compensated In$_{0.52}$Ga$_{0.48}$As/In$_{0.52}$Ga$_{0.48}$As/In$_{0.52}$Al$_{0.48}$As structure. As shown in Fig. 4, a extrapolated f$_g$ of 45-GHz is obtained for the same gate length. It is not surprising that the HEMT fabricated using InAs channel have superior f$_g$, which is primary dominated by the smaller electron effective mass in InAs than that of In$_{0.4}$Ga$_{0.6}$As channel.

4. Conclusion

In conclusion, we have developed a strain-compensated In$_{0.52}$Al$_{0.48}$As/InAs/In$_{0.52}$Al$_{0.48}$As pseudomorphic HEMT. The success of this work is based on the good strain-relaxation buffer layer and suppression of 3-dimensional island growth, using multiple InAs/In$_{0.52}$Al$_{0.48}$As monolayer superlattice 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$_g$ of 51-GHz in a 1.1-μm transistor.

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References