Degradation of pHEMT performance in BiHEMTs caused by thermal history during HBT growth and suggestions for improvement

Junichiro Takeda, Ryota Isono, Shinjiro Fujio, Hiroyuki Kamogawa, Masae Sahara, Takeshi Meguro and *Yohei Otoki

Semiconductor Engineering Department, Hitachi Cable Ltd.,880 Isagozawa, Hitachi, 319-1418, JAPAN
*Hitachi Cable America, 2665 N 1st St. 200, San Jose, CA, 95134
Phone: +81-294-42-5071 E-mail: takeda.junichiro@hitachi-cable.co.jp

Keywords: …pHEMT, MOVPE, BiHEMT, electron mobility, diffusion, uniform doping

ABSTRACT

The use of BiHEMTs, the integration of HBT & pHEMT, have resulted in high efficiency PAs. The mobility of the pHEMT in the BiHEMT structure was lower compared to simple pHEMTs in the development stage. It was found at careful investigation that Si from the delta-doped electron supply layer diffused into the InGaAs channel layer during HBT epitaxial growth. High mobility was obtained in the pHEMT by changing from delta doping to uniform doping.

INTRODUCTION

GaAs/InGaP HBTs are widely used as RF power amplifiers in wireless systems like cellular phones and wireless LANs. Newer phones like smart phones have many functions with multi-bands and multi-modes, which causes higher power consumption and requires large device sizes. GaAs BiFETs which are the monolithic integration of HBTs and FETs [1] have received much attention recently because of their ability to improve the efficiency and reduce the device size through simultaneous processing of HBTs and FETs in one wafer. The integration of the HBT and pHEMT instead of a FET (called BiHEMT here) [2-4] can achieve further high performance by the pHEMT's many advantages like low noise, low threshold voltage and low power consumption [4].

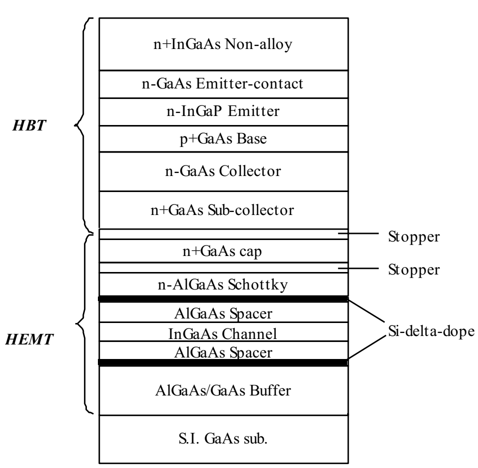

Fig.1 Schematic diagram of BiHEMT structure

In our early development of the BiHEMT epi-wafer, a serious problem occurred where the channel mobility of the pHEMT in BiHEMT was much lower than that of the simple pHEMT:5800 cm^2/Vs versus 7000 cm^2/Vs. The BiHEMT structure is just the combination of pHEMT and HBT and their growth condition is same, just BiHEMT takes longer time. In this paper, the origin of this problem is investigated and the solution is suggested.

EXPERIMENTS

The BiHEMT structure and the simple pHEMT structure as a reference were grown by planetary-type low-pressure MOVPE with face-down system [5]. The carrier gas was H_2 and AsH_3, PH_3, Si_2H_6, H_2Se, TMG, TMA, TMI, TEG and CBr_4 were used as the precursors. Fig.1 shows the structure of BiHEMT we grew here. The structure is a vertical integration of HBT with an InGaP emitter and a pHEMT with an InGaAs channel. The HBT was grown over the pHEMT. A delta-doped electron supply layer was used for the pHEMT, and an etching stop layer was inserted between the HBT and pHEMT. The channel properties of the pHEMT part of the BiHEMT and a simple grown pHEMT were measured by Hall measurement, PL, C-V measurement and SIMS analysis to know what happened in the pHEMT part in BiHEMT.

RESULTS AND DISCUSSIONS

It is well known that electron mobility of pHEMT is influenced by many parameters, such as (1) ionized impurity concentration near channel layer (=doping concentration), (2) carrier concentration in channel (shielding effect and phonon scattering) and (3) quality of InGaAs channel (distortion, defects, purification). We wanted to know what is the main cause of the decreased mobility.

PL profiles at room temperature are shown in Fig.2. The shape of the profile of the BiHEMT is same as that of simple pHEMT, that is, peak energy is same. That means the InGaAs channel layer itself (In concentration and thickness) was not changed. But intensity of BiHEMT was obviously lower than that of pHEMT. The possible reason of this change is the decrease of carrier concentration or the increase of a non-radiative recombination center by some defects or impurity in the channel. We also checked each InGaAs channel by XRD and confirmed that the thickness and In concentration of these two are same, no change.

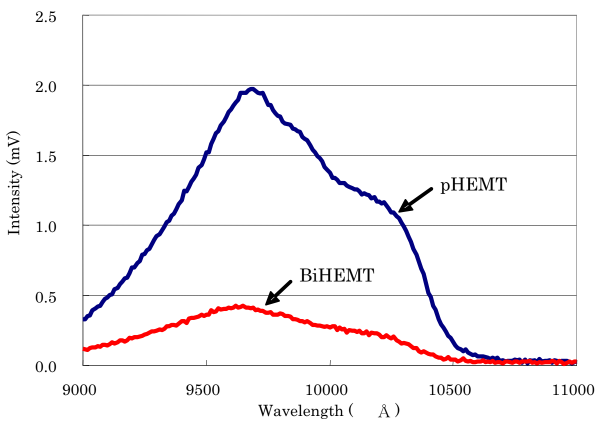

Fig.2 PL profiles of pHEMT in BiHEMT and simple pHEMT

The free carrier concentration measured by Hall measurements showed almost same value and just the mobility of the BiHEMT was low. However, the carrier profiles measured by C-V method were not the same as shown in Fig.3, although the total free carrier concentration obtained by integration of the profile are almost same and agreed with Hall measurement results.

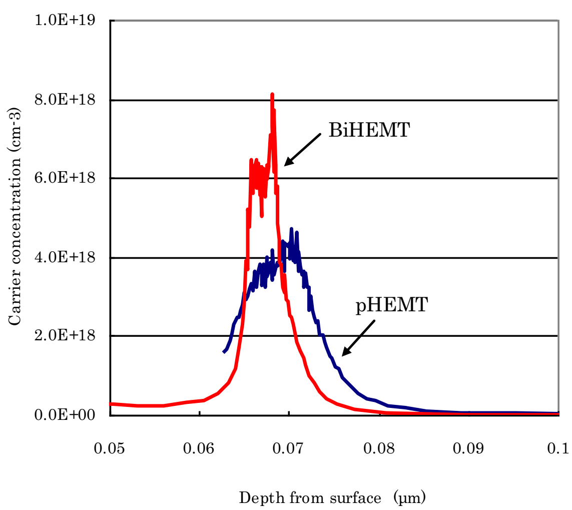

Fig.3 C-V profiles of pHEMT in BiHEMT and Simple pHEMT

We can estimate from these results that the carrier concentration did not decrease, but the potential around channel changed largely in BiHEMT. This potential change must have relation with the degradation of the electron mobility, probably due to increase of some defects or impurities in channel which also work as non-radiative recombination centers.

We did an experiment to clarify the degradation was caused by overall HBT growth itself or just thermal history during the growth of HBT. The simple pHEMT epi-wafers without n+GaAs cap layer were grown and were left in the epi-growth reactor at the same temperature of HBT growth in the AsH_3 atmosphere, that is, pHEMTs were just "annealed" without any growth. Fig.4 showed the dependence of the mobility on the annealing time. The mobility was decreased with annealing time. The C-V profiles showed the similar change we observed in Fig.3. It is obvious that the degradation of pHEMT in BiHEMT is caused by thermal history during HBT growth. We lowered the annealing temperature 80°C. The degradation decreased but was still there as shown by the white circle in the figure. It was surprising results, because we didn't expect the pHEMT was degraded by the temperature of HBT growth which is same or lower than that of pHEMT growth.

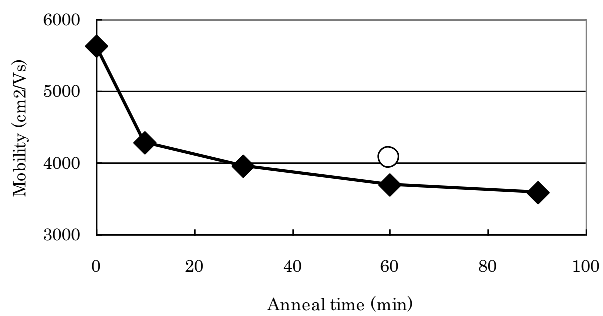

Fig.4 Degradation of mobility by annealing effect
Anneal temperature of ○ was 80C lower than ♦

A careful SIMS analysis has been done for the pHEMT before and after the annealing. Most of the element atoms like In, P and Al were not changed. But Si, an n-type dopant, showed abnormal behavior. Fig.5 is a typical example of the result. The peak profile Si delta-doped layers apparently became broad after the annealing, which means Si diffused abnormally during the annealing and got into the channel. The concentration of the "invaded" diffused Si in the channel is estimated to be E17cm^{-3} range.

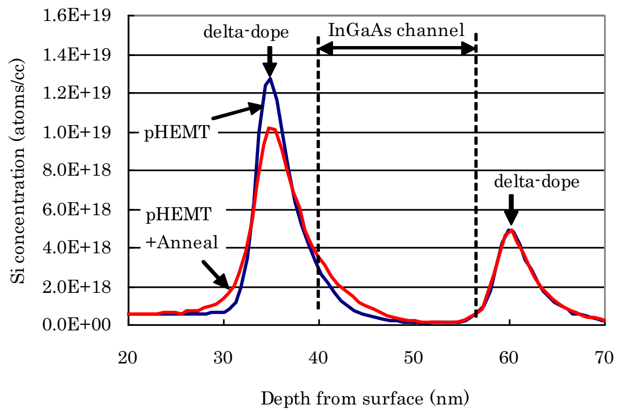

Fig.5 SIMS profile of Si in the pHEMT before and after the annealing

We decreased the doping 20% and examined the degradation caused by the annealing. The degradation was much lower than that of the reference one as shown in Fig.6, although the sheet carrier concentration was lower.

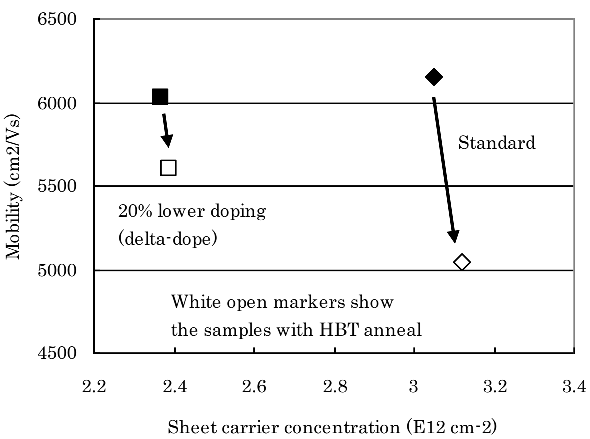

Fig.6 Mobility Degradation of 20% doping decrease pHEMT

These are also surprising results, because Si is well known to have very low thermal diffusion coefficient [6]. In fact, another doping peak with a lower concentration in Fig.5 showed no difference at all, as we normally expected. Taking account of the result of Fig.5 and 6, this abnormal diffusion has some critical point of concentration where the abnormal diffusion occurs. We estimated that delta-doping is a kind of non-equilibrium condition above some density, where Si atoms are then thermally unstable. It's not easy to determine this critical point simply because the diffusion is related with many parameters such as temperature, atmosphere, electrical potential distribution and point defect density, etc.

IMPROVEMENT

Since the cause of the degradation has been made clear, we can suggest some ideas to improve this without changing the HBT growth condition. We show two ideas here.

One is to block the diffusing Si from reaching into the channel layer. One simple way is to increase the spacer layer thickness between the channel and electron supply layer. And another way is to use a uniform doped electron supply layer (supplied layer has some thickness, like 5E18cm^{-3} x 8nm) instead of delta-doping, because the uniform doped supply layer must be in equilibrium and stable. The results of these ideas are shown in Fig.7.

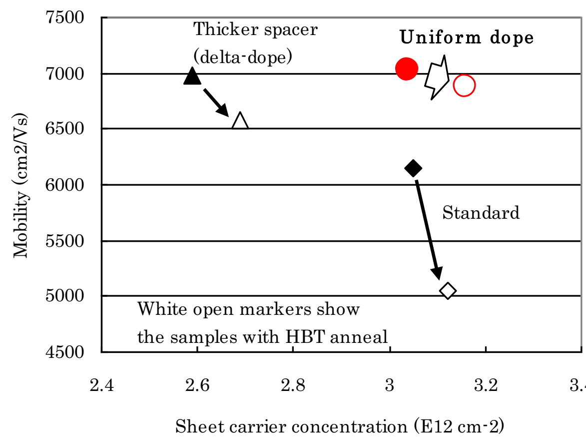

Fig.7 Improvement of ideas by thicker spacer layer and uniform doped

Although the sheet carrier concentration of the thicker spacer layer is lower than that of the reference, the degradation is much smaller. It works. The uniformly doped layer gave us the better results that very low degradation with same sheet carrier concentration.

We probably can make any other ideas based on the investigation results here. We have to take account into this abnormal diffusion when we design the BiHEMT, anyway.

CONCLUSIONS

A BiHEMT structure, which is integration of HBT structure onto pHEMT, had the problem of low electron mobility in the pHEMT. This is because Si in the delta-doped electron supply layer is not stable and diffused into channel during the thermal history of the HBT growth in the BiHEMT. Thicker spacer layer and uniform doped reduced the mobility degradation.

REFERENCES

[1] D. L. Plumton, F. J. Morris and J. Y. Yang, "Method to Integrate HBTs and FETs", U.S. Patent No. 5,077,231 (1989).

[2] M. Shokrani, K Xie, B. Gedzberg, W. Krystek, P. Mushini, A. Gupta, P. Fowler and W Peatman, "InGaP-PlusTM: A Low Cost Manufacturable GaAs BiFET Process Technology", Proc. CS MANTECH Conf., pp. 153-156 (2006).

[3] T. Henderson, J. Middleton, J. Mahoney, S. Varma, T. Rivers, C. Jordan and B. Avrit, "High-Performance BiHEMT HBT / E-D pHEMT Integration", Proc. CS MANTECH Conf., pp. 247-250 (2007).

[4] C. K. Lin, T. C. Tsai, S. L. Yu, C. C. Chang, Y. T. Cho, J. C. Yuan, C. P. Ho, T. Y. Chou, J. H. Huang, M. C. Tu and Y. C. Wang, "Monolithic Integration of E/D-mode pHEMT and InGaP HBT Technology on 150-mm GaAs Wafers", Proc. CS MANTECH Conf., pp. 251-254 (2007).

[5] H. Kamogawa, H. Nagai, K. Takano and Y. Otoki, "Dramatic Reduction of Surface Defects and Particles on pHEMT epi-wafers grown by MOVPE for higher yield of Transistors", Proc. CS MANTECH Conf. (2009).

[6] P. Murugan, R. Pothiraj, S. D. D. Roy and K Ramachandran, "Si diffusion in GaAs", Bull. Mater. Sci., pp. 335-340, vol. 25 (2002).

ACKNOWLEDGEMENT

Authors appreciate Drew Hanser of SRI International for his kind support of reviewing this paper.

ACRONYMS

BiFET: Bipolar Field Effect Transistor
BiHEMT: Bipolar High Electron Mobility Transistor
C-V: Capacity - Voltage
FET: Field Effect Transistor
HBT: Hetero-junction Bipolar Transistor
LAN: Local Area Network
MOVPE: Metal Organic Vapor Phase Epitaxy
PA: Power Amplifier
pHEMT: Pseudomorphic High Electron Mobility Transistor
PL: Photo Luminescence
RF: Radio Frequency
SIMS: Secondary Ion Mass Spectroscopy
XRD: X-Ray Diffraction