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A New HEMT Structure with a Quantum Well Formed by Inserting Monolayers in the Channel

Kohji MATSUMURA, Daijiro INOUE, Haruo NAKANO, Minoru SAWADA,
Yasoo HARADA and Takashi NAKAKADO
Semiconductor Research Center,
SANYO Electric Co., Ltd.
1-18-13 Hashiridani, Hirakata,
Osaka 573, Japan

A new HEMT wafer has been developed whose channel layer has a narrow bandgap semiconductor with a few monolayers inserted at an optimum position in the channel, namely, the point where the probability density of electrons is maximum in the lowest subband and negligible in the first excited subband. The $Al_{0.22}Ga_{0.78}As$/ $In_{0.15}Ga_{0.85}As$ pseudomorphic HEMT wafer with one InAs monolayer inserted at the optimum position has provided Hall electron mobility increments nearly 15% higher at 300 K and 20% higher at 77 K than those of conventional pseudomorphic HEMT wafers.

1. INTRODUCTION

Recently, the performance of AlGaAs/GaAs HEMTs and AlGaAs/InGaAs pseudomorphic HEMTs on GaAs substrates has improved rapidly, which is mainly due to a reduction in their gate lengthes to less than the subhalfmicron order. However, since such reductions will saturate due to the limitation of lithography techniques, it is very important to develop a new design for HEMT wafers which can allow an increase in 2-dimensional electron gas (2DEG) mobility μ_H and its sheet density Ns. A design to fill such requirements is the use of a InGaAs channel layer with a large InAs mole fraction. However, to achieve this design, an epitaxial growth technique has to be developed that can achieve the InGaAs layer with excellent quality and thickness needed for the channel formation, because there is a 7% lattice-mismatch between InAs and GaAs or AlAs[1].

We have developed a new HEMT wafer with one InAs monolayer inserted in the channel which provides superior electrical characteristics to conventional wafers.

In this paper, we discuss the theoretical analysis of electrical states related to developed wafer, its structure and growth conditions, and its measured optical and electrical results.

2. THEORETICAL ANALYSIS

First, we calculated electrical states in the channel of conventional HEMTs, done using both (i) the effective mass

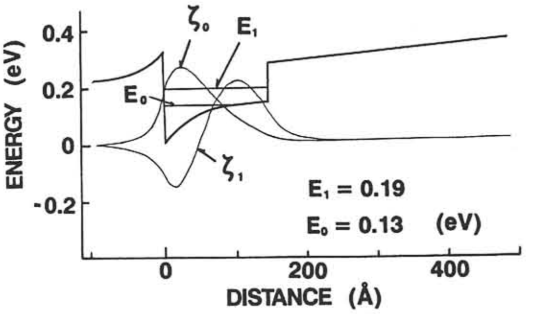


Fig. 1 The wave function, the self-consistent potential and the subband energy of a conventional pseudomorphic HEMT wafer. ζ_0 and ζ_1 represent the envelope wave functions of electrons in the two lowest subbands. E_0 and E_1 indicate the two lowest subband energies from the bottom of the InGaAs conduction band at the AlGaAs/InGaAs interface.

approximation, and (ii) a self-consistent method for solving Poisson's equation and Schrödinger's equation for obtaining an electrostatic potential and an envelope wave function, respectively[2),3)]. Fig. 1 shows the calculated results of a conventional $Al_{0.22}Ga_{0.78}As$ ($n=2\times10^{18}cm^{-3}$, 100Å) / $In_{0.15}Ga_{0.85}As$ (150Å) pseudomorphic HEMT wafer. Calculations were carried out under the assumption that the conduction band offset at the $In_{0.15}Ga_{0.85}As$/GaAs interface is 0.13eV and the electron effective mass of $In_{0.15}Ga_{0.85}As$ is $0.059m_0$[4)]. This result shows that the probability density of electrons at a position d, about 40Å apart from the AlGaAs/InGaAs interface, is maximum in the lowest subband and negligible in the first excited subband.

Based on the results, we calculated electrical states in the channel of a new HEMT wafer, whose channel has one InAs monolayer inserted at the position d=50Å (This position will be describe as the "optimum position" hereafter). Fig. 2 shows the calculated electron energy and density distribution, which was obtained by assuming that the InAs monolayer forms a square quantum well potential with a width of 3Å and a barrier height of 0.47eV in the channel.

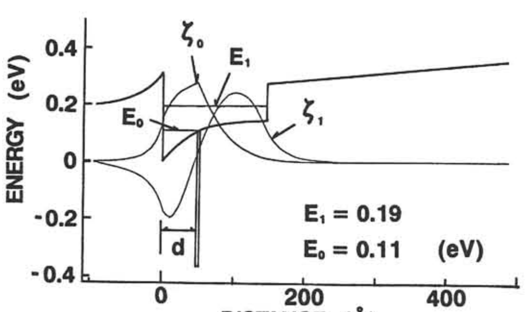


Fig. 2 The wave function, the self-consistent potential and the subband energy of a new pseudomorphic HEMT wafer with an InAs monolayer(d=50Å). "d" is the distance between the AlGaAs/InGaAs interface and the InAs monolayer.

This shows that the InAs layer provides the maximum of the lowest subband's electron distribution ζ_0 at the optimum position and lowers its eigen energy compared with that of conventional wafers at the same position. Futhermore, the layer leaves the electron distribution and energy in the first excited subband nearly unchanged, so that the energy difference in the above two subbands increases compared with those of conventional wafers. These results may very likely provide the following two advantages over conventional wafers. One is an increase in the electron mobility μ_H in the channel, due to (i) the above electron distribution enabling reductions in the scattering between the electrons and remote ionized impurities, since the peak position d=50A is relatively large compared to that of the conventional wafers, and (ii) the energy difference enabling a decrease in intersubband scattering[5),6)]. The other is an increase in the 2DEG sheet density Ns due to a decrease in the lowest subband energy, which can increase the probability density of the electron in the lowest subband, because the energy difference between the lowest subband and the Fermi level increases.

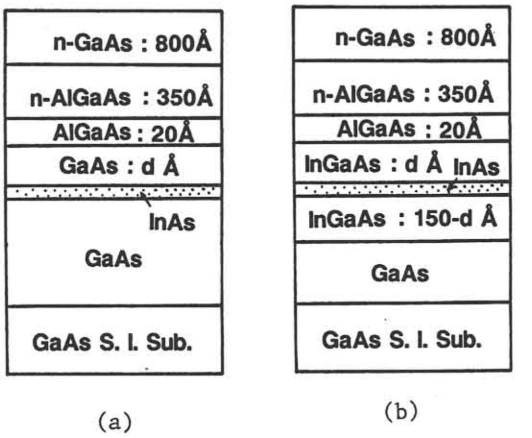


Fig. 3 Wafer structures of a newly developed HEMT. (a) AlGaAs/GaAs system, (b) AlGaAs/InGaAs system.

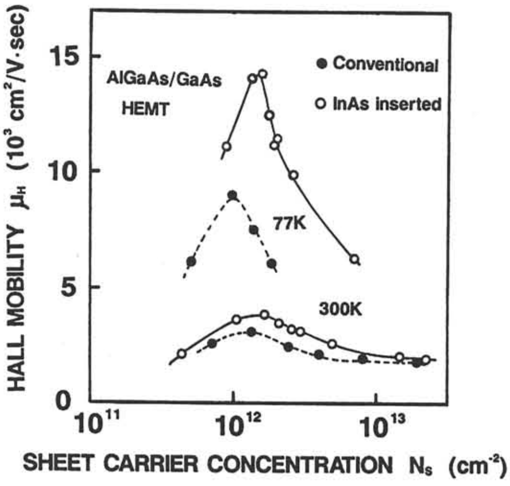
3. WAFER STRUCTURE AND GROWTH CONDITIONS

The following two new wafers were grown using MBE. One is AlGaAs/GaAs HEMT system shown in Fig. 3(a), which has GaAs channel layer(8000Å) with an InAs monolayer inserted at the optimum position, $Al_{0.22}Ga_{0.78}As$ spacer layer(20Å), N-AlGaAs layer($2x10^{18}cm^{-3}$, 350Å), and n-GaAs layer($3x10^{18}cm^{-3}$, 800Å) grown on the S.I. GaAs substrate. The other is an AlGaAs/InGaAs HEMT system as shown in Fig. 3(b), which has the same structure as the above except that it has $In_{0.15}Ga_{0.85}As$ channel layer (150Å) with an InAs monolayer inserted at position d, ranging from 40A to 70A, apart from the AlGaAs/InGaAs interface. The growth temperature and rate were about 510°C and 0.6μm/H, respectively, and each wafer experienced growth interruption for a few minutes in order to improve the surface flatness of InAs layer, that is, the wafer shown in Fig. 3(a) was interrupted at a position of 150Å apart from the AlGaAs/GaAs heterointerface and the other wafer was interrupted at the InGaAs/GaAs interface.

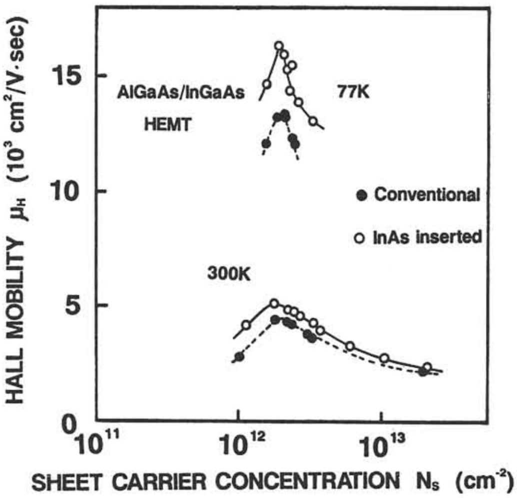
4. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 4(a) and 4(b) show the correlation between the mobility μ_H and the carrier density Ns of the following two new and conventional wafers, which were measured using the van der Pauw method. One is an AlGaAs/GaAs system (Fig. 4(a)) and the other is an AlGaAs/InGaAs system (Fig. 4(b)). These results show that both new wafers with d=50A had a larger mobility μ_H and a slightly larger density Ns compared with those of conventional wafers.

Fig. 5 shows the mobility μ_H of the new AlGaAs/InGaAs system as a function of the inserted InAs monolayer position d. This result shows that (i) the position at d=50A provided the largest mobility, which is higher by 15% at 300K and 20% at 77K than that of the conventional one, and (ii) that the other samples(d=40~70Å) with d>50Å or d< 50A also had a mobility μ_H larger than that of the conventional one. This is because, according to an increase in d (>50Å) not only the lowest subband energy is high but also the change in its electron distribution is small, which causes an increase in the above mentioned two mode scatterings. Also, according to a decrease in d (<50Å), the peak position of the electron distribution in the



(a)



(b)

Fig. 4 The correlation between Hall mobility μ_H and sheet density Ns. (a) AlGaAs/GaAs system, (b) AlGaAs/InGaAs system. The open circle indicates a new HEMT wafer with an InAs layer (d=50Å), and the closed circle indicates a conventional HEMT wafer.

lowest subband shifts towards the N-AlGaAs layer which results in an increase in the above mentioned remote ionized impurity scattering.

2DEG density Ns of the wafer with d=50A ranged from $1.75\times10^{12}cm^{-2}$ to $1.85\times10^{12}cm^{-2}$, which was obtained from the Shibnikov-de Haas oscillation measurement.

Fig. 6 shows the photoluminescence (PL) spectra of the new AlGaAs/InGaAs pseudomorphic HEMT wafer with d=50Å, as well as the conventional one, which was measured in order to investigate the above mentioned reductions in the lowest subband energy. A red emission peak shift was observed from only in the new structure, and corresponded to this reduction.

Therefore, preliminary experimental results agree with the above mentioned theoretical analysis. A more remarkable increase in 2DEG mobility μ_H and sheet density Ns is possible by inserting (i) a few InAs monolayers into one position in the channel or (ii) one InAs monolayer into a few positions and (iii) a semiconductor layer with a much smaller bandgap than that of InAs, which is derived from our preliminarily theoretical analysis.

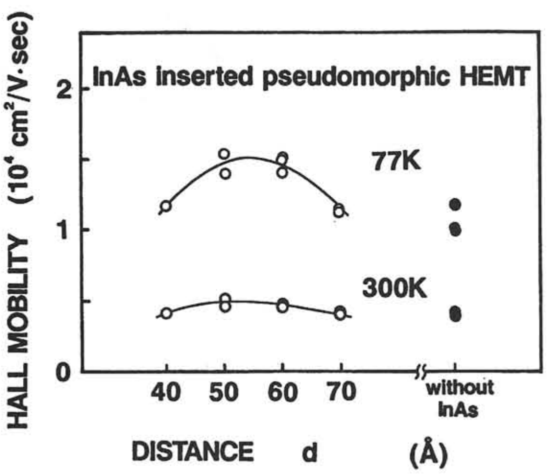


Fig. 5 The correlation between an InAs monolayer position and maximum Hall mobility for an AlGaAs/InGaAs HEMT structure.

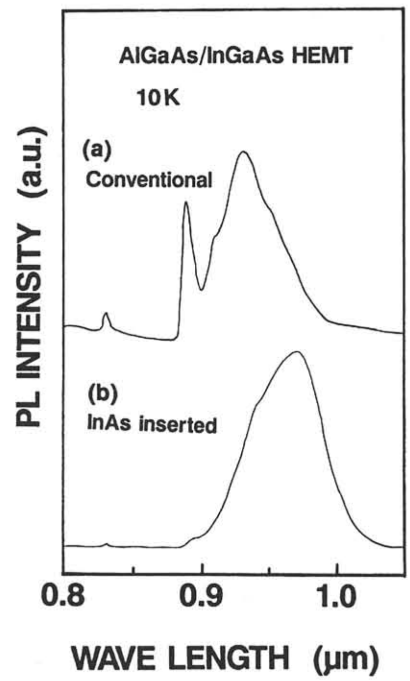


Fig. 6 Photoluminescense spectra from AlGaAs/InGaAs pseudomorphic HEMT at 10K. (a) and (b) indicate a conventional and a newly designed wafer, respectively.

5. CONCLUSION

We have succeeded in the preliminary design and fabrication of a new HEMT wafer with a quantum well formed by inserting one InAs monolayer in the channel, and have demonstrated experimentally an increase in 2DEG mobility and sheet density in the channel which agrees with the theoretical calculations including the InAs insertion position.

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