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Enhancement of Mobility in Pseudomorphic FET's with Up and Down Monolayers

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Single molecular InAs and AlAs layers (monolayers) were inserted in quantum wells by MBE in order to improve electron transport. Carrier confinement in the channel is enhanced significantly and the subband energy separation is increased by inserting the monolayers in appropriate positions in the quantum well. PL and Hall measurements confirmed the energy level shifts and the mobility enhancement due to the monolayer insertions.

In recent reports[1-5] a single molecular plane of different species is epitaxially inserted into a host quantum well to shift the wavefunctions and energy levels in a controlled manner. By utilizing appropriate band gap alignments between the monolayer and the host, one can create a "down" monolayer, such as InAs in GaAs where a deep localized potential well is embedded in the host, or an "up" monolayer, such as AlAs in GaAs where a thin potential barrier is installed. The "down" and "up" monolayers can also be grown in combination to achieve special goals. For example, a "down" monolayer can enhance wavefunction confinement in a heterojunction field effect transistor (HFET) quantum well channel. Carrier concentration is increased and parasitic parallel conduction in the supply layers and buffer layers is reduced because more carriers are located in the active channel layer. If one "down" and one "up" monolayers are placed near the appropriate peak positions of the wavefunctions of the ground and first excited states of a quantum well respectively, the subband energy level separation is increased and inter-subband scattering is reduced. Further separations in higher order states can be obtained with additional "up" monolayers. In this way, the mobility of the channel region can be enhanced. We present simulation and experimental results on three HFET structures with or without InAs or AlAs monolayers.

Sample MBE214 is a pseudomorphic HFET with a 150Å $In_{0.15}Ga_{0.85}As$ quantum well channel, 300Å $Al_{0.3}Ga_{0.7}As$ supply layer, Si-doping plane (5×10^{12} cm^2), 40Å spacer, and 50Å n^+ GaAs cap layer (5×10^{18} cm^3) (Fig. 1a). MBE224 has an InAs monolayer inserted inside the $In_{0.15}Ga_{0.85}As$ channel about 42Å away from the interface (Fig. 1b) and MBE209 has two additional AlAs monolayers inserted near the back side of the quantum well channel (Fig. 1c). The AlAs monolayers are located at the positions of the n = 2, 3 wavefunctions maxima. The samples were grown in a Vacuum Generators V80H MBE system on 3" semi-insulating GaAs (100). Source materials were elemental 8N gallium (Rhone Poulenc), 6N5 indium (Johnson Matthey, 6N aluminum (Cominco) and 7N arsenic (Furakawa). The substrates were first boiled in trichloroethane and acetone, ultrasonically rinsed in propanol and etched in H_2SO_4:H_2O_2:H_2O. They were then mounted on the holders and outgassed at 300°C prior to insertion into the growth chamber. Growth rates and alloy compositions were calibrated using reflection high energy electron diffraction (RHEED). Growth rates of 0.81 and 0.34 monolayers per second for GaAs and AlAs respectively were used. The In composition was 0.15 for InGaAs layers and the Al composition was 0.3 for AlGaAs layers. The As_4/Ga flux

ratio (from beam equivalent pressures) was taken to be approximately 3. The growth temperature was measured with an optical pyrometer which was periodically calibrated against the GaAs oxide desorption temperature. A 0.75 μm GaAs buffer layer was grown at 525°C andthe growth of InAs monolayers was done at approximately 500°C.

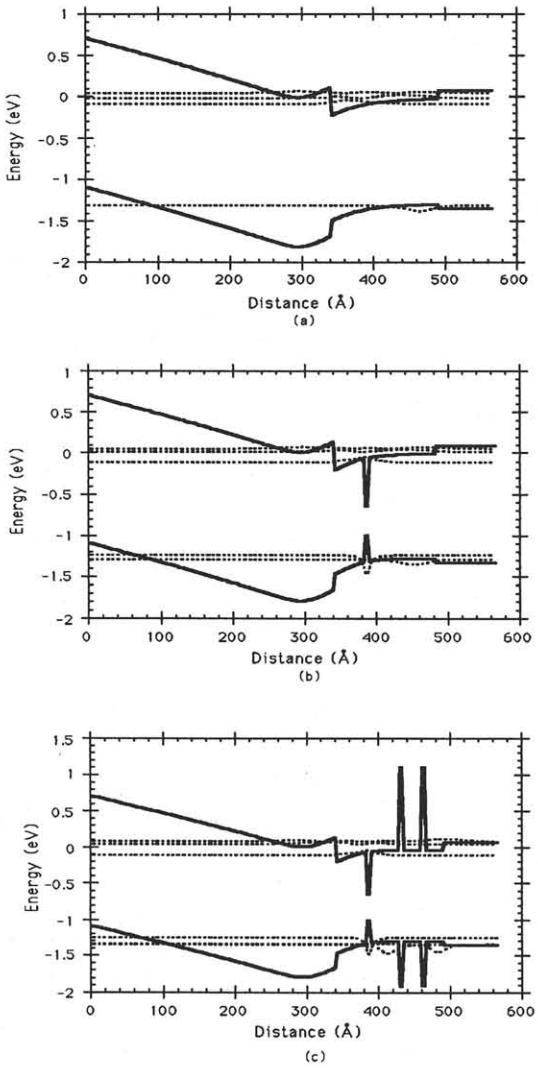

Figure 1. Bandstructures, energy levels and wavefunctions of the three samples: MBE214 (a), MBE224 (b) and MBE209 (c). Thick lines are profiles of the valence and conduction band edges. Horizontal lines indicate the eigenstate energies of the system. Deviations from the horizontal lines represent the squares of the corresponding eigenfunctions.

We calculated the energy levels, wavefunctions, and carrier distributions in the supply and channel layers by solving the Schrödinger and Poisson equations selfconsistently. The δ-doping was simulated by a Gaussian distribution to account for Si diffusion. We set the surface and back side potentials to 0.7 eV and set the Fermi level to zero as the reference energy. The ground state energies, first subband level separations and the channel and supply layer electron concentrations are listed in Table I for comparison.

TABLE I. Simulation results of the three HFET structures.

	E_0	E_1-E_0	n(channel)	n(supply)
Sample	(eV)	(eV)	(10^{12}cm^{-2})	(10^{12}cm^{-2})
MBE214	-0.089	0.075	2.74	0.26
MBE224	-0.107	0.124	2.91	0.15
MBE209	-0.114	0.150	2.87	0.16

As expected, the quantum well ground state energy decreases when the InAs monolayer is inserted to the peak position of the wavefunction. The sheet carrier density in the channel increases by about 6% and the supply layer sheet carrier density decreases by about 40%. For sample MBE209, two AlAs monolayers are positioned to increase the intersubband separations between the ground state and the first two excited states. From the calculation, we find that the increase in separation of the first two bands for MBE209 is 100% over MBE214 and 21% over MBE224. The ground state of MBE209 is lower than that of MBE214 because the slightly larger channel width (by about 9Å) of the test sample. Figure 2 shows 4K photoluminescence data. The data confirmed the downward shift in energy with the insertion of the InAs monolayer; however, the amount of shift is less than expected for a full monolayer [1]. This can be explained by partial 2-D coverage of the InAs plane prior to the subsequent deposition of the $In_{0.15}Ga_{0.85}As$ layers. The transition energy for MBE209 falls in the expected range although the peak position is not very well resolved.

The temperature dependence of mobility is shown in Fig. 3. Matsumura et al. observed mobility enhancement of about 15% at 300K and about 20% at 77K for one InAs monolayer in the pseudomorphic channel [4]. At room temperature we observed little difference between the three samples. At low temperatures there is approximately a 15% improvement in mobility due to the fractional down monolayer. For

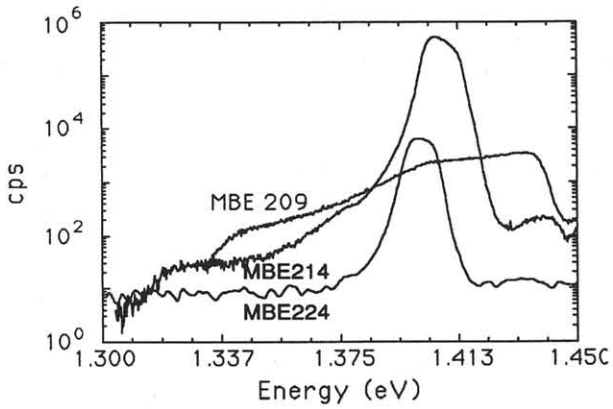

Figure 2. Photoluminescence data (4K) for the three samples.

two AlAs up monolayers, there is nearly twice the improvement in mobility at low temperatures. This is a factor of three greater than the improvement using one down monolayer [4]. The mobility of MBE209 is independent of the temperature below ~100K. This is due to the screening of ionized impurities in the supply layer by the degenerate 2-dimensional electron gas system[6].

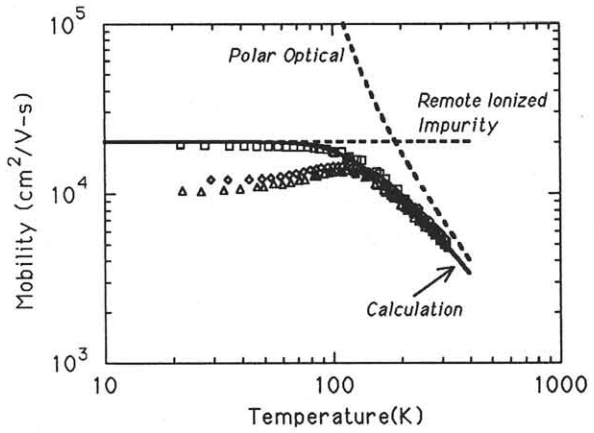

Figure 3. Temperature dependent Hall data for the three samples. Triangles-MBE214, Diamonds-MBE224, Squares-MBE209.

The mobilities of MBE214 and MBE224 decrease at temperatures below 100K. In the bulk semiconductor, the ionized impurity scattering dominated mobility has a temperature dependence of $T^{3/2}$. We observed a slope of $T^{1/3}$ for the two samples, which indicates that the supply layers in this sample are not totally depleted. The depletion of carriers in the supply layer is dependent on the surface potential of the samples. This value is approximately 0.7 eV. As is well known, the mobility is limited by the polar-optical phonon scattering at high temperature and limited by a temperature independent remote ionized impurity scattering (degenerate 2DEG) at low temperature [6]. We used

$$\mu_{PO} = \frac{6.3 \times 10^8}{T^2} + \frac{9.44 \times 10^{16}}{T^6} \ (\mathrm{cm^2/V \cdot s}) \quad (1)$$

for the polar-optical mobility to account for the fact that $\mu \sim 1/T^6$ near 77K [7] and $\mu \sim 1/T^2$ near 300K [8]. The mobility due to remote ionized impurity scattering was chosen to fit the data $\mu_{RI}=2.4\times10^4$ $cm^2/V\cdot s$. The total mobility is, according to the Matthiessen's rule, $\mu=(1/\mu_{RI}+1/\mu_{PO})^{-1}$. A good fit between the data and the model was obtained as shown in Fig. 3.

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References

[1] M. Sato and Y. Horikoshi, J. Appl. Phys. **66** (1989) 786, Appl. Phys. Lett. **56** (1990) 1555

[2] W. Trzeciakowski and B. D. McCombe, Appl. Phys. Lett. **55** (1989) 891

[3] A. Uddin and T. G. Andersson, J. Appl. Phys. **65** (1989) 3101

[4] K. Matsumura, D. Inoue, H. Nakano, M. Sawada, Y. Harada, T. Nakanado, Extended Abstracts of 22nd Intl. Conf. on Solid State Dev. and Mat., Sendai (1990) 35

[5] Kenji Shiraishi and Eiichi Yamaguchi, Phys. Rev. B **42** (1990) 3064

[6] K. Lee, M. S. Shur, T. J. Drummond, and H. Morkoç, J. Appl. Phys. **54** (1983) 6432

[7] D. L. Rode, Phys. Rev. B **2**, (1970) 1012

[8] T. J. Drummond, H. Morkoç, and A. Y. Cho, J. Appl. Phys. **52**, (1981) 1380