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QUANTUM WELL AND MODULATION DOPED GaAs - Ga$_{1-x}$Al$_x$As HETEROSTRUCTURES

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Résumé. - MOVPE est appliqué à la réalisation de puits quantiques Ga$_{1-x}$Al$_x$As - GaAs. Des puits aussi étroits que 25 Å sont obtenus. La qualité des interfaces est caractérisée par photoluminescence en fonction de la raideur des transitions de concentration d'aluminium. Aucun désordre d'alliage n'est observé. On met en évidence un accord remarquable entre les énergies de transition électron-trou lourd (n = 1) et celles calculées à partir d'un simple modèle de puits rectangulaire. Les résultats montrent que la transition GaAlAs-GaAs s'effectue en moins de 5 Å.

Des hétérostructures à dopage modulé ont été obtenues dans des conditions de croissance similaires. Des résultats préliminaires sur la mobilité de Hall et des caractéristiques de TEC seront présentés.

Abstract. - Ga$_{1-x}$Al$_x$As - GaAs quantum wells are grown by MOVPE. Wells as narrow as 25 Å are made. Interface quality in relation to alloy clustering and abruptness in change of Al-content is characterized with the aid of luminescence spectrum measurements. A remarkable agreement is found between the experimental n = 1 electron to heavy hole transition energies and those which are calculated with the simple rectangular well model. The results indicate that the Al content changes at the interfaces over less than an unit cell.

Modulation doped heterostructures were made in the same growth conditions as used for the quantum well growth. Results of Hall mobility measurements and preliminary FET characteristics are shown.

1. Introduction. - GaAlAs-GaAs multilayer heterostructures have recently become a subject of intensive study. Fundamental aspects, such as the study of a 2D electron gas at an abrupt heterojunction interface and practical applications, such as the 2D electron gas FET and quantum well lasers, are of great interest. MBE is now the standard growth method associated with abrupt and high quality interfaces. An alternative for this technique may be metal organic vapour phase epitaxy (MOVPE) at atmospheric pressure, attractive because of its simplicity. We have grown by MOVPE, using the same growth conditions, both quantum wells to check the achieved heterojunction abruptness and its quality by photoluminescence, and single period modulation doped heterostructures to assess the mobility enhancement and show the feasibility of a heterojunction FET with this material.

2. Experimental Results and Discussion.

2.1. Quantum wells. - We used Ga(CH$_3$)$_3$, Al(CH$_3$)$_3$, AsH$_3$ and H$_2$ as a carrier gas. The growth temperature was 650°C, the reactor pressure 1 atm., the growth rate 5 Å/sec. The wells were made in continuous growth. The gas transport in the reactor was arranged so as to be able to change the gas composition over the wafer in a controlled way within 0.1 sec.

Holonyak et al. have made MOVPE-grown quantum wells. They made notably a structure of two GaAs wells 40 Å wide, separated by a 40 Å Ga$_{1-x}$Al$_x$As barrier and between Ga$_{1-x}$Al$_x$As cladding layers. The photoluminescence spectrum showed a broad peak at the energy corresponding to the n = 1 electron...
to heavy hole single particle transition for a $40 \, \text{Å}$ well and a hill smeared out between the $n = 1$ transition energies for a $40 \, \text{Å}$ and for a $120 \, \text{Å}$ well, related to local interaction between the two wells. The deviation of the spectrum from one sharp peak was attributed to alloy clustering.

Miller and Tsang\textsuperscript{2)}, who repeated the experiment with MBE showed that alloy clustering in ternary barriers is not necessarily present in MBE grown material. We show here that it can also be avoided in MOCVD grown layers. The same epitaxial structure, but with $25 \, \text{Å}$ wells as shown in fig. 1, was grown on a semi-insulating Cr doped substrate. The substrate orientation was $(100)$ tilted $6^\circ$ off. The sample was excited at $4 \, \text{K}$ with a CW argon laser at $5145 \, \text{Å}$. The excitation power density was $0.4 \, \text{W/cm}^2$. Fig. 1 shows the obtained spectrum. The width of the peak is $10.5 \, \text{mV}$. No luminescence is traced in the region between the peak and the substrate luminescence. The same experiment was also done with one well which gave essentially the same spectrum. A sample with no well at all, but just a $1.3 \, \mu\text{m}$ thick Ga$_{0.46}$Al$_{0.54}$As layer showed no trace of luminescence in the region of interest.

![Photoluminescence spectrum of two 25 Å GaAs quantum wells separated by a 40 Å thick Ga$_{0.46}$Al$_{0.54}$As barrier and with 1 um thick ternary layers on either side. The sample temperature was 4 K.](image)

**Fig. 1**: Photoluminescence spectrum of two 25 Å GaAs quantum wells separated by a 40 Å thick Ga$_{0.46}$Al$_{0.54}$As barrier and with 1 um thick ternary layers on either side. The sample temperature was 4 K.

Fig. 2 shows the calculated relation between wavelength and well width corresponding to the $n = 1$ electron to heavy hole transition energy for a perfectly rectangular well, taking for the electron effective mass in the GaAs as a function of energy:\textsuperscript{3)}

$$m^*_e = (0.0665 + 0.0436 E + 0.236 E^2 - 0.147 E^3) \, m_0$$ \hfill (1)

with $E$ in eV.

The electron effective mass in the Ga$_{1-x}$Al$_x$As\textsuperscript{4)} is taken as:

$$m^*_e = (0.067 + 0.083 x) \, m_0$$ \hfill (2)

and the hole effective mass in both materials\textsuperscript{4)}:

$$m^*_hh = (0.48 + 0.31 X) \, m_0$$ \hfill (3)
The bandgap of GaAs at 4 K is 1.5192 eV. The band discontinuities are:

\[ V = p (1.247 x + 1.147 (x - 0.45)^2) \]

with \( p = 0.85 \) for the conduction band and \( p = 0.15 \) for the valence band.

FIG. 2: Calculated relation between emission wavelength and GaAs well width, corresponding to the \( n = 1 \) electron to heavy hole transition for a rectangular well with \( \text{Ga}_{0.46}\text{Al}_{0.54}\text{As} \) barriers.

In order to estimate the abruptness in change of Al-content at the interfaces, we have grown a layer of \( \text{Ga}_x\text{Al}_{1-x}\text{As} \) containing four GaAs layers of 30 Å, 45 Å, 70 Å and 100 Å thickness (Fig. 3). The Al mole fraction \( x \) was found by double X-ray diffraction to be 0.54. The thicknesses of the layers are deduced from steady state growth speed determined by step measurements on thicker layers of GaAs and GaAlAs in which patterns were selectively etched, and from SIMS depth profiling of a ten period 30 Å well 30 Å barrier GaAs - Ga\text{As}_{0.46}\text{Al}_{0.54}\text{As} superlattice on top of a 100 Å well 100 Å barrier superlattice which showed a genuine 3 to 10 ratio of lattice periods. The result of this last measurement discounts the possibility of a growth rate variation when the interface is grown, leading to, for example, an extra thickness of GaAs which would alter the 3 to 10 ratio of lattice periods.

FIG. 3: Four GaAs wells of different sizes grown in one sample.
Fortunately, a measurement of lattice periods does not require such a high resolution as a direct measurement of interface abruptness by SIMS.

Fig. 4 shows the measured luminescence spectrum of the four well sample. The arrows indicate the places where the peaks should be according to the calculation of fig. 2. The band to band luminescence of the semi-insulating substrate is not visible on this sensitivity scale because of the abundance of mid band levels in such a substrate.

![Photoluminescence spectrum of the heterostructure of fig. 3, measured at 4 K. The arrows indicate the places where the peaks should be according to the calculation of fig. 2. The sample was excited with an Ar laser at 5145 Å. Incident power density was 0.4 W/cm².](image)

If the Al-content were to change gradually at the interfaces, the wavelength versus well width relation would be modified. To estimate the size of this modification in the case of the four wells of 30, 45, 70 and 100 Å, a simple model was chosen in which the Al content as a function of its z position is described by:

\[
x' = \begin{cases} 
  x & z \leq 0 \\
  x e^{\frac{z}{L_t}} & 0 < z < d \\
  x(1-e^{-\frac{z-d}{L_t}}) & z \geq d
\end{cases}
\]

As \( L_t \) increases, the luminescence peak shifts to a shorter wavelength for a given well width \( d \).
Fig. 5 shows the result of a calculation which made use of direct numerical integration of the Schrödinger equation to find the real (unperturbed) states. The shift for a narrow well appears to be much larger than for a large well. Comparing figures 4 and 5, we find that $L_t$ for our interfaces is smaller than 5 Å.

The drawing shows the assumed exponential composition profile with characteristic transition width $L_t$.

**Fig. 5**: Luminescence peak shift to shorter wavelength of fig. 2 in the case of a non-abrupt transition in Al content at the interfaces.

### 2-2. Modulation doped structures.

- Considerable mobility enhancement at a GaAs–Ga$_{0.5}$Al$_{0.5}$As interface has already been obtained by Coleman et al. 5.

Using different optimized growth temperatures for the growth of GaAs and GaAlAs layers, resp. 615°C and 750°C, and selenium as a dopant, they achieved a Hall mobility of 45 000 cm$^2$/Vs at 77 K.

In our case, n-doping of the GaAlAs was realized by introduction of SiH$_4$ in the gas mixture. Single accumulation layer structures were made, with a 1500 Å thick Ga$_{0.5}$Al$_{0.5}$As layer doped at about 7.5·10$^{17}$ at/cm$^3$ Si except for a 80 Å thick non-intentionally doped Ga$_{0.7}$Al$_{0.3}$As spacer next to the interface with the 0.5 um thick non-intentionally doped GaAs layer underneath. We used a semi-insulating Cr-doped substrate, oriented (100) tilted 6° off. The reactor and the growth conditions were the same as those used for the quantum wells: a constant temperature of 650°C and a growth speed of 6 Å/sec. We did not interrupt the growth at the interfaces. The Si doping level might be somewhat inaccurate due to calibration problems and the strong temperature dependence of Si incorporation.

Hall measurements were done by the van der Pauw method, using clover-shaped samples in a magnetic field of 1800 Gauss. The 77 K Hall mobilities were found to be in the 70 000 - 80 000 cm$^2$/V·sec. region, the best wafer exhibiting a Hall mobility of 6700 cm$^2$/V·sec. at 300 K and 80 000 cm$^2$/V·sec. at 77 K with a mobile carrier concentration per unit area of 8.3·10$^{11}$/cm$^2$ at 77 K, deduced from the Hall measurement. The 77 K value exceeds the Hall mobility of a simple GaAs layer. A 3 μm thick non-intentionally doped GaAs layer grown on a semi-insulating chromium doped substrate just before the heterojunction experiment yielded Hall mobilities of 7500 cm$^2$/V·sec. and 44 000 cm$^2$/V·sec. at resp. 300 K and 77 K, with a free electron concentration of 1.7·10$^{15}$/cm$^3$ at 300 K and 77 K.
A MESFET process has been carried out on a non-optimized wafer with the same heterojunction structure as above but with a spacer of 50 Å, a Ga$_{0.7}$Al$_{0.3}$As layer of 900 Å doped at about 5.10$^{17}$ at/cm$^3$ Si exhibiting a Hall mobility of 45000 cm$^2$/V.sec. at 77 K and 5200 cm$^2$/V.sec. at 300 K with a mobile carrier concentration of 8.10$^{11}$ at./cm$^2$ at 77 K. The aluminium gate has a length of 100 μm and a width of 1000 μm. The source-gate and drain gate spacings are 1 μm. Source and drain are Au-Ge alloyed ohmic contacts. The obtained characteristics are shown in fig. 6. The threefold increase of transconductance as temperature falls from 300 K to 77 K indicates clearly the enhanced mobility effect. Comparison of channel mobility, Hall mobility of this wafer and best Hall mobility results leads to the conclusion that the FET is not yet optimal.

![Image of graphs showing transconductance characteristics](image)

**FIG. 6 :**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$V_{g\text{max}}$</th>
<th>300K</th>
<th>77K</th>
</tr>
</thead>
</table>

3. **Conclusion**

Growth of narrow quantum wells has been shown to be feasible with MOVPE at atmospheric pressure. Experimental spectra show narrow luminescence peaks at energies consistent with the simple rectangular well model. Although ternary barriers were used, alloy clustering has not been observed. Al content is estimated to change at the interfaces typically within a unit cell.

Single period modulation doped GaAs - Ga$_{0.7}$Al$_{0.3}$As heterostructures made in the same growth conditions exhibit two-dimensional electron Hall mobilities up to 6700 cm$^2$/V.sec. at 300 K and 80 000 cm$^2$/V.sec. at 77 K exceeding bulk mobility. The feasibility of a heterojunction FET with the material is shown.

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