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THE EFFECT OF ARSENIC SPECIES ON THE MINORITY CARRIER PROPERTIES OF (AlGa)As-GaAs DOUBLE HETEROSTRUCTURES GROWN BY MBE

G. Duggan, P. Dawson, C.T. Foxon and G.W. 't Hooft*

Philips Research Laboratories, Redhill, England
*Philips Research Laboratories, Eindhoven, The Netherlands

Abstract - The influence of arsenic molecular species, As$_2$ or As$_4$, on the minority carrier properties of beryllium doped, p-isotype (AlGa)As-GaAs double heterostructures has been studied. All the samples were grown at 650°C in an oil diffusion pumped system with extensive liquid nitrogen cryopanelling and vacuum interlock. The same batch of arsenic was used to prepare both the As$_2$ and As$_4$ films. The choice of active layer thickness (1 μm) and doping level (N$_{A\text{D}}$ = 5x10$^{16}$ cm$^{-3}$) ensured the sensitivity of the minority carrier lifetime to the properties of the (AlGa)As-GaAs interfaces. Measurements of the minority carrier lifetime in the GaAs performed using a photoluminescence decay technique showed the advantage of using As$_2$ for the ternary cladding regions. Supplementary measurements of the external photoluminescence efficiency, under low excitation conditions, allowed us to estimate the interface recombination velocity at the (AlGa)As-GaAs interface and to place a minimum value (>6%) on the internal photoluminescence efficiency of the GaAs. We conclude that for alloys grown with As$_2$, the interface recombination velocity is at least a decade lower than equivalent films grown with As$_4$.

Introduction - In successfully growing low threshold current (AlGa)As/GaAs double heterostructure (DH) lasers by Molecular Beam Epitaxy (MBE) [1], Tsang has attached much importance to the need to grow good quality (AlGa)As/GaAs interfaces where the concentration of deep centres in the vicinity of the heterobarrier is low, thus reducing the loss of carriers via non-radiative recombination by tunnelling to these centres [2]. This non-radiative recombination path is usually characterised

Résumé.- Nous avons étudié l'influence des espèces moléculaires d'arsenic : As$_2$ ou As$_4$ sur les propriétés des porteurs minoritaires de doubles hétérostructures (AlGa)As-GaAs, isotope p, dopé beryllium. Tous les échantillons ont été élaborés à 650°C dans un système de vide à pompe à diffusion avec des panneaux cryogéniques d'azote liquide et un système d'introduction rapide. Le même lot d'arsenic a été utilisé pour les flux moléculaires As$_2$ et As$_4$. L'épaisseur de la couche active (1 μm) et le niveau de dopage (N$_{A\text{D}}$ = 5x10$^{16}$ cm$^{-3}$) ont été choisis pour que la durée de vie des porteurs minoritaires soient en rapport avec les propriétés des interfaces (GaAl)As-GaAs. Les mesures de durée de vie des porteurs minoritaires dans GaAs par une technique de dégradation de photoluminescence ont montré qu'il est meilleur d'utiliser As$_2$ pour les régions ternaires. Des mesures supplémentaires du rendement de photoluminescence externe sous des conditions de faible excitation nous ont permis d'estimer la vitesse de recombinaison à l'interface (AlGa)As-GaAs et de fixer une valeur minimale (>6%) au rendement de photoluminescence interne de GaAs. Nous concluons que, pour les composés élaborés avec As$_2$, la vitesse de recombinaison d'interface est plus faible au moins d'une décennie que celle des couches équivalentes obtenues avec As$_4$.

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in terms of the interface recombination velocity which is said to exist at the heterobarrier. Therefore in order to produce low threshold current heterostructure lasers it is necessary, but probably not sufficient, to reduce this interface recombination velocity as far as is physically possible. One possible means of reducing this quantity is the subject of this investigation.

The use of the arsenic dimer, \text{As}_2, as opposed to the \text{As}_4 molecular species has been clearly demonstrated as producing a significant reduction in the concentrations of those traps (M1, M3, M4) which are characteristic of MBE GaAs [4,5]. In addition Kunzel and Ploog [6] claim that the use of the dimer produces material whose optical quality is as good as LPE grown GaAs. In the light of this evidence a logical step, in our opinion, was to see if the use of \text{As}_2 in growing (AlGa)As/GaAs DHs resulted in a subsequent improvement in the interface recombination velocity \( S \). For this purpose (AlGa)As isotype DHs were grown with appropriate combinations of \text{As}_2 and \text{As}_4 in the active and cladding layers and their minority carrier properties studied using both transient and steady state photoluminescence techniques.

Growth Procedure - All the samples for this study were grown in a fully automated, diffusion pumped, three chamber MBE system in which the substrate is almost entirely surrounded by a liquid nitrogen cooled cryopanel. \text{As}_2 was produced using a special two zone furnace or cracker [4], conventional BN or graphite crucibles were used for all other species. After loading and baking the system, the room temperature external photoluminescence (PL) efficiency of GaAs layers improves progressively (see fig. 1) until a plateau is reached after \( \approx 10^{-15} \) microns of material have been deposited. Using measurements on a stepped [7] Sn doped layer grown in this phase (T47) and on a subsequently grown Be doped, stepped sample we have established that the internal quantum efficiency is \( \approx 10\% \) at this stage. All the DHs studied were grown after this initial "clean-up" stage. In addition to monitoring the GaAs quality we have also looked at the room temperature PL of the (AlGa)As alloy layers grown in this system. In fig. 2 we compare the 300 K PL spectra of n-type Al_{0.2}Ga_{0.8}As layers grown with both \text{As}_2 and \text{As}_4. Although both spectra exhibit "deep" emission its presence is far more marked in the \text{As}_4 spectrum than that grown with the dimer and the absolute level of the PL from this layer (of the same thickness and doping level) is lower than that of the \text{As}_2 grown sample.

Table 1 illustrates the growth sequences employed for the four Be doped DHs used in this study. Growth was carried out using a substrate temperature of 650°C with Al, Ga, As, \text{As}_2 and \text{As}_4 fluxes of \( 3\times10^{14} \), \( 6\times10^{14} \), \( 1\times10^{15} \), and \( 1\times10^{15} \) mol cm\(^{-2}\) s\(^{-1}\) respectively using a calibrated ion gauge to set the required cell temperatures. The same batch of arsenic was used to load both the \text{As}_2 and \text{As}_4 cells. A Be cell, calibrated by previous measurements of doping in p-type GaAs, was used to give a flux of 1.5\times10^8 atoms cm\(^{-2}\) s\(^{-1}\). Sample thicknesses were checked by an optical interference technique and Hall measurements indicated that all four structures were doped at \( \approx 5\times10^{16} \) cm\(^{-3}\). Room temperature PL and subsequent X-ray measurements showed that the Al content in the cladding regions was \( \approx 30\% \). Lightly doped samples, where diffusion lengths are usually \( \gg 1 \) micron, were chosen for this study to maximise the sensitivity to interface effects; p-type films were used to minimise problems with interface and surface band bending and to avoid any incorporation problems with n-type doping where the free carrier concentration is influenced more readily by growth conditions.
Fig. 1 Improvement in external PL efficiency after loading and baking MBE system.

Fig. 2 External 300 K PL measurements of (AlGa)As \((n \approx 3 \times 10^{18} \text{ cm}^{-3})\) grown from (a) As\(_4\) and (b) As\(_2\).
### Results and Discussion

The effective lifetime, $t_{\text{eff}}$, of minority carriers in the GaAs active region of each of the four DHs was measured directly by monitoring the decay of the front surface photoluminescence signal following optical excitation using short duration (<500 ps) pulses at 752 nm from a mode-locked Kr+ laser [8]. In Table 2 we show the measured electron lifetime for the four samples studied. It is clear from this table that there appears to be a significant advantage in using the dimer for the growth of the (AlGa)As cladding regions.

#### Table 1: Growth sequence of p isotype DHs

<table>
<thead>
<tr>
<th>Thickness ($\mu$m)</th>
<th>$N_A - N_D$ (cm$^{-3}$)</th>
<th>Arsenic species used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding AlGaAs</td>
<td>1.5</td>
<td>3 x 10$^{16}$</td>
</tr>
<tr>
<td>Active GaAs</td>
<td>1.0</td>
<td>5 x 10$^{16}$</td>
</tr>
<tr>
<td>Cladding AlGaAs</td>
<td>1.5</td>
<td>3 x 10$^{16}$</td>
</tr>
<tr>
<td>Buffer GaAs</td>
<td>0.5</td>
<td>$\approx 10^{16}$</td>
</tr>
<tr>
<td>Substrate GaAs</td>
<td>250</td>
<td>Cr doped</td>
</tr>
</tbody>
</table>

#### Table 2

<table>
<thead>
<tr>
<th>Sample numbers</th>
<th>Measured $t_{\text{eff}}$ (n sec)</th>
<th>$n_{\text{ext}}$ ($10^{-3}$)</th>
<th>$L_e$ ($\mu$m)</th>
<th>$S$ (cm s$^{-1}$)</th>
<th>Calculated $t_{\text{eff}}$ (n sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/2/2</td>
<td>5.4</td>
<td>1.0</td>
<td>8.0</td>
<td>5 x 10$^2$</td>
<td>6.0</td>
</tr>
<tr>
<td>2/4/2</td>
<td>5.4</td>
<td>7.0 x 10$^{-4}$</td>
<td>6.4</td>
<td>5 x 10$^2$</td>
<td>3.9</td>
</tr>
<tr>
<td>4/2/4</td>
<td>1.3</td>
<td>1.7 x 10$^{-4}$</td>
<td>8.0</td>
<td>4 x 10$^4$</td>
<td>1.8</td>
</tr>
<tr>
<td>4/4/4</td>
<td>1.1</td>
<td>1.4 x 10$^{-4}$</td>
<td>6.4</td>
<td>4 x 10$^4$</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The minority carrier lifetime consists of two components:

$$\frac{1}{t_{\text{eff}}} = \frac{1}{t_b} + 2S/d$$  

(1)

where $t_b$ is the bulk minority carrier lifetime, $S$ the interface recombination velocity (assumed equal at either interface) and $d$ is the active layer thickness. As we have already established that the GaAs is relatively efficient and thus likely to satisfy the condition that the minority carrier diffusion length $L$ is much greater than the layer thickness, one could immediately conclude that the improvement in lifetime was due only to a reduction in recombination velocity. However, we should note that the estimates of internal efficiency were made at higher doping levels where due to a shorter radiative lifetime in both n and p-type material [9,10] the effect of non-radiative centres in the bulk will be smaller. Therefore we performed supplementary steady state, 300 K PL measurements to confirm that the improvement in $t_{\text{eff}}$ could be attributed to a reduction in $S$. 

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**Table 1:** Growth sequence of p isotype DHs

**Table 2**

The minority carrier lifetime consists of two components:
The absolute external PL efficiency, \( \eta_{\text{ext}} \), of the four structures was measured using a previously calibrated PL system \([11]\). An excitation density of \( \sim 0.3 \) Watts cm\(^{-2}\) at 752 nm was used to provide injection conditions close to those under which the lifetime was determined. Values of the measured \( \eta_{\text{ext}} \) are also presented in table 2. The external PL efficiency, under low excitation conditions and neglecting reabsorption effects, can be related to the minority carrier diffusion length and interface recombination velocity through the following relationship \([12]\)

\[
\eta_{\text{ext}} = \frac{L^2}{D} \cdot \frac{N_{S,0}}{N_{0,0}}
\]  

(2)

where \( t_r \) is the radiative lifetime and \( N_{S,0}, N_{0,0} \) are complicated functions of both \( S \) and \( L \) \([12]\). Using the right hand side of (2) it is possible to generate a family of curves as a function of \( L \), with \( S \) as the varying parameter. Then if the value of \( t_r \) is known at the appropriate doping level \([10]\) together with the diffusion coefficient \([11]\) it is possible to calculate the expected efficiency for the structures as a function of \( S \) and \( L \). The results of the calculation are in figure 3. Also plotted are the \( \eta_{\text{ext}} \) values for the four structures. The possible range of values for \( S \) and \( L \) are given by the coincident points of the calculated and measured values, these are indicated by the solid, horizontal lines in figure 3.

\[ \text{Fig. 3: Measured and calculated values of } \eta_{\text{ext}} \text{ for DH samples studied.} \]

Let us now make the reasonable assumption that \( L \) remains a constant for the GaAs grown with a particular type of arsenic molecule. It is now possible to make estimates of the minimum values of \( L \) and \( S \) which are consistent with the observed values of \( \eta_{\text{ext}} \). These are listed in table 2 together with the calculated effective lifetime for this combination of \( S \) and \( L \). Reasonable agreement exists between the measured and calculated values. From these minimum values we can estimate the internal efficiency of the lightly doped p-type GaAs for both the As\(_2\) and As\(_4\) films of about 10\% and 6\% respectively. The inescapable conclusion is that the use of As\(_2\) significantly improves the interface recombination velocity.
We note at this point that these are clearly not the only \( S \) and \( L \) combinations that will fit the observations. However, an upper limit on the diffusion length (\( \sim 28 \) microns) is set by the radiative lifetime \( (7.7 \times 10^{-8} \text{ sec} \ [10]) \) of the material. In addition the family of curves will tend to become flat (especially those where \( S \) is large) as the diffusion length increases significantly \([12]\). All this serves to illustrate that even though the values quoted in table 2 may not be exact the qualitative relationship between the \( S \) values has to remain unchanged and that there is at least a factor of 10 improvement in using \( \text{As}_2 \) in the cladding regions of the \( \text{DHs.} \)

Acknowledgements - We are grateful to Dr George Scott for suggesting the experiment and to Mr Jim Neave for assistance in the design of the MBE equipment.

References