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Magneto-Hall characterization of delta-doped pseudomorphic high electron mobility transistor structures

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Conventional Hall-effect determination of the two-dimensional electron gas (2DEG) concentration \( n_{2D} \) in pseudomorphic high electron mobility transistor structures is invalid because of interference from the highly doped GaAs cap. Furthermore, the usual methods of dealing with this interference problem, namely, (1) etching off the cap totally, (2) etching the cap until the mobility reaches a maximum, or (3) growing a separate structure with a thin, depleted cap, in general, give \( n_{2D} \) values that are too low. However, we show here that magnetic-field-dependent Hall (M-Hall) measurements can separately determine the carrier concentrations and mobilities in the cap and 2DEG regions, as verified by comparison with a self-consistent, four-band, \( \mathbf{k} \cdot \mathbf{p} \) calculation and also by electrochemical capacitance-voltage measurements in structures with different cap and spacer thicknesses.

INTRODUCTION

The pseudomorphic high electron mobility transistor (pHEMT), basically consisting of a strained In\(_{x}\)Ga\(_{1-x}\)As channel layer, an Al\(_{x}\)Ga\(_{1-x}\)As doping layer (usually a sheet or “delta” charge close to the In\(_{x}\)Ga\(_{1-x}\)As), and a GaAs contact layer, all on a semi-insulating (Si) GaAs substrate, has emerged as the device of choice for power microwave devices in the 30–100 GHz range and for many high-speed digital applications. Thus, accurate electrical characterization of the pHEMT is critical, and among the most important parameters are the mobility \( \mu_{2D} \) and sheet carrier concentration \( n_{2D} \) of the two-dimensional electron gas (2DEG) in the In\(_{x}\)Ga\(_{1-x}\)As well. Unfortunately, the GaAs cap layer, which is highly doped to permit good ohmic contacts, can dominate a standard Hall-effect measurement, since usually \( n_{\text{cap}}>n_{2D} \). To circumvent this problem, some workers simply etch off the cap so that only the 2DEG remains; we will show that this procedure gives an erroneous result. Another common method is to grow a separate structure, identical except that the cap is only 50 Å thick and thus depleted. This technique also gives an incorrect result and, moreover, is costly because a separate wafer must be grown. A third alternative, also costly because it is time-consuming and labor-intensive, is to etch off the GaAs cap layer in small steps until the measured mobility is at a maximum value. The assumptions in this latter case are, evidently, that the maximum mobility in the etching sequence is equal to the 2DEG mobility before etching, and that the carrier concentration at the point of maximum mobility is the same as that before etching. We will show that at least the second of these assumptions is incorrect.

Recently we introduced a new method (M-Hall) which gives \( \mu_{2D}, n_{2D}, \mu_{\text{cap}}, \) and \( n_{\text{cap}} \) without removing the conducting cap layer. This method simply requires performing standard resistivity and Hall-effect measurements at two or more magnetic fields and then applying an exact, analytical formulation to get \( \mu_{2D}, n_{2D}, \mu_{\text{cap}}, \) and \( n_{\text{cap}} \). Other solutions to this problem, based on the same initial equations, have either been approximate or fully numerical. In the original work, the M-Hall technique was applied to HEMT structures uniformly doped in the Al\(_{x}\)Ga\(_{1-x}\)As region; here, we apply it to delta-doped (Δ-doped) pHEMT structures. The results agree well with a self-consistent, four-band, \( \mathbf{k} \cdot \mathbf{p} \) calculation, discussed in detail elsewhere.

Another method often applied to highly-doped, multilayer structures is electrochemical capacitance-voltage (EC-V) profiling. In a companion publication we show that EC-V profiling can reproduce the general features of pHEMT material quite well. Here, we simply demonstrate that the EC-V data are consistent with M-Hall and theoretical results.

EXPERIMENTAL DETAILS

Four pHEMT wafers, with structures shown in Fig. 1, were used in this study. They were grown in a Varian Gen II molecular beam epitaxial apparatus using solid-source As, with an As\(_{2}/\text{Ga} \) beam equivalent pressure ratio of about 15. Each structure had a Si δ-doping of \( 4 \times 10^{12} \) cm\(^{-2} \), but the spacings between the δ-doped layer and the In\(_{x}\)Ga\(_{1-x}\)As well varied from 45–180 Å so that the amount of charge that transferred from the δ layer to the In\(_{x}\)Ga\(_{1-x}\)As well also varied. A further charge of about \( 1 \times 10^{12} \) cm\(^{-2} \) in the doped Al\(_{x}\)Ga\(_{1-x}\)As layers above and below the well was also available for transfer to the well, but part of the upper charge went to the GaAs cap. To study variations of electrical properties with respect to cap thickness, an etch solution comprised of 1:1 1 molar C\(_{6}\)H\(_{8}\)O\(_{7}\):30% H\(_{2}\)O\(_{2} \) was used to partially or totally remove the cap of the structure with a 45 Å
GaAs:Si 4x10^{18} \text{cm}^{-3} 350 \text{Å}

Al_{0.26}Ga_{0.74}As:Si 2x10^{17} \text{cm}^{-3} 240 \text{Å}

Si-delta 4x10^{12} \text{cm}^{-2}

Al_{0.24}Ga_{0.76}As 45 \text{Å}

In_{0.22}Ga_{0.78}As 125 \text{Å}

Al_{0.24}Ga_{0.76}As 50 \text{Å}

Al_{0.24}Ga_{0.76}As:Si 9x10^{17} \text{cm}^{-3} 50 \text{Å}

Al_{0.24}Ga_{0.76}As 200 \text{Å}

GaAs 15 \text{Å}

12 periods

GaAs 16 \text{Å}

GaAs 10,000 \text{Å}

Semi-insulating GaAs substrate

FIG. 1. Nominal structure of the pHEMT materials used in this study.

spacer. One sample had 80 Å (out of 350 Å) removed from the cap, and another had the full cap removed. The 80 Å removal was calibrated by the shift of the 2DEG peak in the EC-V measurements. The various structures studied are listed in Table I. Two separate wafers with 350 Å caps and 45 Å spacers were grown to check reproducibility. One of these was used in the etch study.

The M-Hall technique was developed to separate the effects of two conductive bands or layers in a sample by making use of the magnetic-field (B) dependence of the resistivity ρ and Hall coefficient R that arise in such systems.3 It has been shown to work well in regular Al_{x}Ga_{1-x}As/GaAs HEMTs. Fortunately, the single-carrier, or single-layer, magnetic-field dependences in these structures as well as in pHEMT structures are negligible, as has been explicitly shown, because the carriers in both the cap and 2DEG regions are basically degenerate. It also might be argued that the pHEMT really consists of three conductive layers, the cap, δ charge and 2DEG. However, the mobility in the δ region is very low, ~10^2 cm^2/V s, as measured on a separate structure so that the δ conductance is much smaller than the cap and 2DEG conductances. Thus, the M Hall method, applied to a pHEMT structure, can determine μ_{2D}, n_{2D}, μ_{cap}, and n_{cap}. In practice, we have found that μ_{cap} and n_{cap} can often not be separately determined with nearly as much accuracy as their product, ρ_{cap}=ρ_{cap} \mu_{cap} n_{cap}. This is not a severe problem because μ_{cap} is similar for most n^{+}-GaAs cap layers, i.e., μ_{cap}=1500±500 cm^2/V s, nearly independent of temperature. Thus, for comparison with theory, we have used the M-Hall value of ρ_{cap} along with μ_{cap}=1500 cm^2/V s to determine n_{cap}. It should also be noted that, from a practical point of view, the value of ρ_{cap} alone is normally sufficient for characterization purposes. The M-Hall results are listed in Table I.

For the analysis here, magnetic fields of 2, 10, and 16 kG were used to determine the ρ vs B and R vs B dependences although, in principle, only two values of B would have been needed. Sufficiently good signal-to-noise in typical pHEMTs can be obtained with a field as low as 10 kG for 296 K data, and possibly as low as 5 kG for 77 K data. However, the higher fields are preferable if they are available.

Standard capacitance-voltage (C-V) measurements, commonly used to determine concentration profiles in semiconductor materials, have been shown to accurately portray the electron configuration in GaAs δ-doped layers without the usual Debye-length limitations in resolution.11 Other studies have dealt with simple Al_{x}Ga_{1-x}As/GaAs heterostructures in which there is electron transfer at the interface.12 However, standard C-V measurements, in which a stepped reverse bias voltage is used to progressively widen the depletion region in the sample, cannot be applied to HEMT or pHEMT structures because, at high reverse biases, the high electric field in the cap causes carrier multiplication and breakdown. Fortunately, the electrochemical C-V (EC-V) method has been developed for such situations, although

### TABLE I. Comparison of M-Hall measurements with theory.

<table>
<thead>
<tr>
<th>Wafer No.</th>
<th>Spacer (Å)</th>
<th>Cap (Å)</th>
<th>T (K)</th>
<th>2D conc. (10^{12} \text{cm}^{-2})</th>
<th>2D mob. (cm^2/V s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>350</td>
<td>296</td>
<td>5.4</td>
<td>7.6</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>350</td>
<td>296</td>
<td>5.7</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>350</td>
<td>296</td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>350</td>
<td>296</td>
<td>2.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Theory only</td>
<td>45</td>
<td>50</td>
<td>296</td>
<td>0.9</td>
<td>0</td>
</tr>
</tbody>
</table>

aUsing M-Hall value for ρ_{cap} and assuming μ_{cap}=1500 cm^2/V s.

bPossibly not all of cap removed by etch.

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there are few reports on its use in pHEMT structures. In the EC-V technique, the bias is usually held at zero or at a low value as the layer is successively etched away to simulate increasing reverse bias. Recently, we have shown that EC-V profiles reproduce not only the cap and 2DEG regions well, but also the S region. In Fig. 2, we show EC-V data for structures with 45 Å (solid line) and 180 Å (dashed line) spacer layers, respectively, and both the S and 2D regions are clearly reproduced, with less charge being transferred to the In$_{x}$Ga$_{1-x}$As well in the latter case, as expected. For the sample with a 45 Å spacer, the two regions are not as well separated; however, the total integrated electronic charge in both regions, about 4.5×10$^{12}$ e/cm$^{2}$, agrees well with the theoretical result to be discussed.

**DISCUSSION**

M-Hall and theoretical results are compared in Table I. The theoretical 2DEG concentration is integrated from the minimum at about a 600 Å depth through the tail at about 800 Å. The average difference between theoretical and M-Hall 2DEG concentrations is only 6%, which must be considered excellent since the theory relies on nominal thicknesses, concentrations, and x values. As expected, agreement is not as good for the cap concentrations, with an average discrepancy of about 20%. The average difference would be reduced if there were a GaAs/Al$_{x}$Ga$_{1-x}$As interface depletion of 1–2×10$^{12}$ cm$^{-2}$, but it is more likely that the M-Hall results for the cap are simply not accurate to a greater degree than this. As confirmation, note that wafers 1 and 2 are supposedly identical, yet the M-Hall cap concentrations at 296 and 77 K differ by about 27% on average. Note also, however, that the M-Hall values of $n_{cap}$ do not depend, within error, on spacer thickness, and that they decrease approximately by the expected amount after the 80 Å etch. Thus, the M-Hall method is adequately characterizing the cap layer, although without the good accuracy found for the 2DEG layer.

Next, consider the effects of spacer thickness, as seen by the comparison of wafers 2, 3 and 4. M-Hall, EC-V, and theory all show much less electron transfer as the spacer is increased from 45 to 180 Å. As a practical matter, note that $n_{2D}$ decreases by 44% at 296 K, whereas $\mu_{2D}$ (Table I) increases by only 13%. Thus, from a 296 K device point of view, smaller spacers are probably better because they give a higher overall conductance. At 77 K, $\mu_{2D}$ increases by about 42% so that the advantage of a smaller spacer is not as great.

Finally, note from Table I that as the cap is etched off, $n_{2D}$ drops from 3.1 to 1.8×10$^{12}$ cm$^{-2}$. The reason, apparent from the band diagrams in the etched case (which are not shown in Fig. 3 to improve clarity), is that the In$_{x}$Ga$_{1-x}$As well must compete with the surface acceptor states (now much closer) for the $d$ electrons. Thus, the practice of etching
off the cap so that a standard Hall measurement can be performed gives an erroneous result for \( n_{2D} \). However, \( \mu_{2D} \) is not as affected, at least in this case, as is seen in Table I. Another common method to avoid the cap-conductance problem is growth of a separate structure with a 50 Å, doped GaAs cap layer, which will presumably allow good contacts to be made but will still be totally depleted due to the surface acceptor states. However, as seen from the theoretical result at the end of Table I, \( n_{2D} \) is still considerably lower than it is with a 350 Å cap, again because of the relative location of the surface states. The same considerations hold for the method, described earlier, in which the cap is etched back until the measured mobility (by standard Hall measurements) is a maximum. If most of the cap is etched off at this point, the measured \( n_{2D} \) will be too low. The M-Hall technique circumvents all of these problems by allowing accurate measurements of both \( n_{2D} \) and \( \mu_{2D} \) while the cap is still in place.

The temperature dependences of \( n_{2D} \) seen in Table I result both from band-structure and Boltzmann-factor considerations that favor the lower energy states (In\(_x\)Ga\(_{1-x}\)As well) at lower temperatures. On average, the M-Hall \( n_{2D} \) values are slightly higher at 77 K than 296 K, in agreement with the theory; however, the small differences are within the error of the M-Hall technique. The mobilities (Table I) are, of course, strongly temperature dependent which demonstrates the large advantage of pHEMTs over the competitive GaAs metal-semiconductor field-effect transistors (MESFETs) for low-temperature operation.

**SUMMARY**

We have applied the new M-Hall technique to pHEMT structures and shown that it agrees well with \( EC-V \) measurements and \( k-p \) theory. It appears that the M-Hall method is both more accurate and more economical than alternative methods for electrical characterization of pHEMT structures.

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