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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 cap-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 $In_xGa_{1-x}As$ channel layer, an $Al_xGa_{1-x}As$ doping layer (usually a sheet or "delta" charge close to the $In_xGa_{1-x}As$), 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.[1] Thus, accurate electrical characterization of the pHEMT is critical, and among the most important parameters are the mobility μ_{2D} and sheet carrier concentration n_{2D} of the two-dimensional electron gas (2DEG) in the $In_xGa_{1-x}As$ well. Unfortunately, the GaAs cap layer, which is highly doped to permit good ohmic contacts, can dominate a standard Hall-effect measurement, since usually $n_{cap} \gg n_{2D}$. 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.[2] 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 μ_{2D}, n_{2D}, μ_{cap}, and n_{cap} without removing the conductive cap layer.[3] This method simply requires performing standard resistivity and Hall-effect measurements at two or more magnetic fields and then applying an exact, analytical formalism to get μ_{2D}, n_{2D}, μ_{cap}, and n_{cap}. Other solutions to this problem, based on the same initial equations, have either been approximate[4] or fully numerical.[5–7] In the original work,[3] the M-Hall technique was applied to HEMT structures uniformly doped in the $Al_xGa_{1-x}As$ 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.[8,9]

Another method often applied to highly-doped, multilayer structures is electrochemical capacitance-voltage (EC-V) profiling. In a companion publication[10] 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_4/Ga beam equivalent pressure ratio of about 15. Each structure had a Si δ-doping of 4×10^{12} cm^{-2}, but the spacings between the δ-doped layer and the $In_xGa_{1-x}As$ well varied from 45–180 Å so that the amount of charge that transferred from the δ layer to the $In_xGa_{1-x}As$ well also varied. A further charge of about 1×10^{12} e/cm^2 in the doped $Al_xGa_{1-x}As$ 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 $C_6H_8O_7$:30% H_2O_2 was used to partially or totally remove the cap of the structure with a 45 Å

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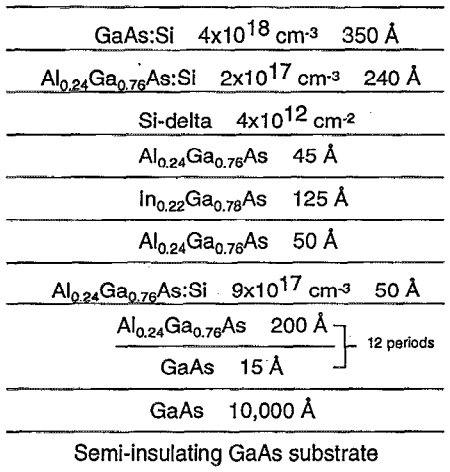

FIG. 1. Nominal structure of the *p*HEMT materials used in this study.

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) dependences of the resistivity ρ and Hall coefficient R that arise in such systems.[3] It has been shown to work well in regular $Al_xGa_{1-x}As/GaAs$ HEMTs. Fortunately, the single-carrier, or single-layer, magnetic-field dependences in these structures as well as in *p*HEMT 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 *p*HEMT really consists of three conductive layers, the cap, δ charge and 2DEG. However, the mobility in the δ region is very low, $\sim 10^2$ 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 *p*HEMT 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, $\sigma_{cap}=\rho_{cap}^{-1}=e\mu_{cap}n_{cap}$. This is not a severe problem because μ_{cap} is similar for most n^+-GaAs cap layers, i.e., $\mu_{cap}=1500\pm500$ 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 $\mu_{cap}=1500$ 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 *p*HEMTs 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 $Al_xGa_{1-x}As/GaAs$ 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 *p*HEMT 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.

Wafer No.	Thickness: Spacer (Å)	Thickness: Cap (Å)	T (K)	Cap conc. (10^{12} cm^{-2}): M-Hall[a]	Cap conc. (10^{12} cm^{-2}): Theory	2D conc. (10^{12} cm^{-2}): M-Hall	2D conc. (10^{12} cm^{-2}): Theory	2D mob. (cm^2/V s) M-Hall
1	45	350	296	5.4	7.6	3.1	3.0	6,600
			77	5.7	7.6	3.2	3.2	17,000
		270	296	3.6	4.4	2.9	3.0	6,300
		(etched)	77	2.5	4.4	3.2	3.2	16,200
		0[b]	296	0.9[b]	0	1.8	2.0	6,100
		(etched)	77	0.9[b]	0	1.9	2.0	16,900
2	45	350	296	6.6	7.6	3.2	3.0	6,200
			77	8.0	7.6	3.2	3.2	14,400
3	90	350	296	6.0	7.6	2.5	2.2	6,600
			77	7.7	7.4	2.3	2.4	16,300
4	180	350	296	5.7	7.7	1.8	1.5	7,000
			77	7.4	7.4	1.8	1.6	20,500
Theory only	45	50	296		0		2.4	

[a]Using M-Hall value for ρ_{cap} and assuming $\mu_{cap}=1500$ cm^2/V s.
[b]Possibly not all of cap removed by etch.

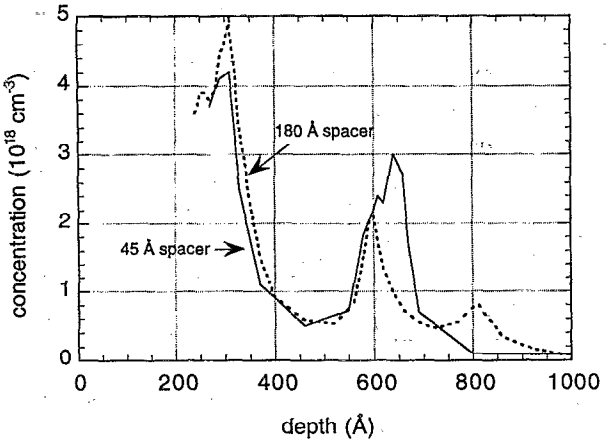

FIG. 2. Electrochemical C-V profiles of pHEMT samples with different spacer layer thicknesses: (—), 45 Å spacer; (----), 180 Å spacer. Details of the structure are given in Fig. 1.

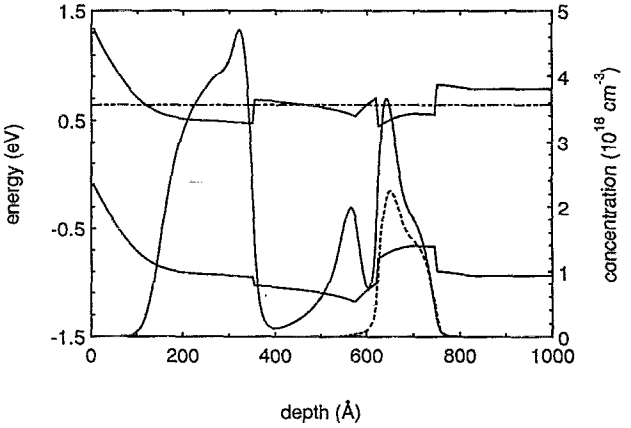

FIG. 3. Self-consistent $\mathbf{k}\cdot\mathbf{p}$ calculation of the bands and electron concentration of a pHEMT sample with a 350 Å cap and a 45 Å spacer layer. Details of the structure are given in Fig. 1. Also shown is the electron concentration only (----) of the same structure except with the cap removed. Note that, in the latter case, the δ region is almost completely devoid of electrons, and the well region much reduced. The chained line is the Fermi level.

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 δ region.[10] 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 δ and 2D regions are clearly reproduced, with less charge being transferred to the $In_xGa_{1-x}As$ 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.

THEORY

Modeling of the structures in Fig. 1 was accomplished with a four-band, $\mathbf{k}\cdot\mathbf{p}$ calculation of the band structure, coupled self-consistently with a solution of the Poisson equation.[8,9] The eigenstates were described in a basis consisting of electron, heavy-hole, light-hole, and split-off bulk states. The strain Hamiltonian in this basis is quite detailed and includes strain-induced band mixing as well as strain-induced corrections to the spin-orbit interaction. The exchange-correlation potential was calculated from density-functional theory within the local-density approximation. Surface donor and acceptor states were included to pin the surface Fermi level at about $E_C-0.7$ eV, which is known to occur for a free surface of GaAs. Interface states were not included because the EC-V results (Fig. 2) do not show a large depletion at the $GaAs/Al_xGa_{1-x}As$ interface. The theoretical band and concentration profiles of a structure with a 45 Å spacer are shown as solid lines in Fig. 3. Also shown, as a dotted line, is the concentration profile of a sample with the cap removed. Clearly both the δ and 2DEG concentrations are reduced in the latter case, because some of the δ electrons are transferred to surface acceptor states instead of the $In_xGa_{1-x}As$ well.

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 $GaAs/Al_xGa_{1-x}As$ interface depletion of $1-2\times10^{12}$ 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 μ_{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, μ_{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 $In_xGa_{1-x}As$ well must compete with the surface acceptor states (now much closer) for the δ 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, μ_{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.[2] 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 μ_{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 ($In_xGa_{1-x}As$ 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 *p*HEMTs over the competitive GaAs metal-semiconductor field-effect transistors (MESFETs) for low-temperature operation.

SUMMARY

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

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