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Analytical Two-Layer Hall Analysis - Application To Modulation-Doped Field-Effect Transistors

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The classical magnetic-field-dependent Hall coefficient and conductivity equations are inverted to give the mobilities μ_1 and μ_2 and carrier concentrations n_1 (or p_1) and n_2 (or p_2) in two degenerate bands. The two-band solution holds for arbitrary magnetic-field strength as long as quantum effects can be ignored (i.e., $kT > \hbar eB/m^*$), and it is argued that the analysis can also be applied to two separate layers up to reasonable field strengths. The results are used to determine the two-dimensional electron gas mobility and carrier concentration in a modulation-doped field-effect transistor with a highly doped cap layer.

INTRODUCTION

The modulation-doped field-effect transistor (MODFET), based on carrier transfer from a highly doped high-band-gap material to an undoped lower-band-gap material, is now one of the dominant devices in high-speed applications.[1] The most common form of this device consists of GaAs as the undoped channel layer, then $Al_{0.3}Ga_{0.7}As$ (written as AlGaAs hereafter) as the doping layer, and finally a highly doped GaAs layer ("cap" layer) on top for ohmic contacting purposes. Ideally, all of the current in the final device will be carried in the undoped GaAs layer because the mobility is highest there, and by etching off a portion of the top two layers in the channel region, this situation can often be achieved. However, a problem arises in assessing the initial material by Hall-effect measurements, one of the most common characterization tools, because all three layers can contribute to both the conductivity and Hall coefficient. This is often called the "parallel conduction" problem, and because of its importance has been addressed in many publications.[2–9] However, even though the well-known classical magnetic-field equations[10] are often the starting point in these various works, they are either numerically fitted to the data[5] or approximated to get an analytical two-band solution at small magnetic fields.[9] In this paper, we solve the equations to get an exact analytical two-band solution which holds at arbitrary magnetic field B as long as the carriers are degenerate and quantum effects can be ignored, i.e., if $kT > \hbar eB/m^*$. The exact solution is much more useful than an approximate low-B solution, because high values of B give better signal to noise, and it is also obviously more useful than a numerical fit to the original equations because the latter requires a four-parameter fit.

Experimentally, we show that even though there are three possible conductive layers in MODFET structures, only the two GaAs layers are important, especially at lower temperatures, because the donors (DX centers) in $Al_{0.3}Ga_{0.7}As$ are about 60 meV deep, reducing thermal excitation to the conduction band. Thus, a two-layer analysis is sufficient. We also show that the individual layers have very small B dependences on their own, so that the measured large B dependence arises mainly from two-layer (mixed-conductivity) effects.

Finally, we need to consider differences between two-band and two-layer problems. In a single-layer, two-band problem both bands obviously experience exactly the same potential at a given position in the sample. In a two-layer problem, however, in which the layers are electrically isolated, the only guaranteed equipotential points between the two layers are at the contacts.[11] For less than perfect isolation, an intermediate situation will exist. There is theoretical and experimental evidence that the distinction between two-band and two-layer models vanishes at small magnetic fields, including our field range (0–1.6 T).[12] Also, we believe that there is direct experimental evidence that our analysis is basically correct, because the 2D electron concentrations are nearly equal at 296 and 77 K, as they should be, even though the relative layer characteristics vary widely at these two temperatures.

THEORY

The equations expressing the dependences of conductivity σ and Hall coefficient R on magnetic field B for two degenerate (i.e., relaxation time τ independent of energy) bands have been known for many years[10] and are more recently derived in, e.g., Ref. 13:

$$\sigma=\frac{(\sigma_1+\sigma_2)^2+\sigma_1^2\sigma_2^2(R_1+R_2)^2B^2}{(\sigma_1+\sigma_2)+\sigma_1\sigma_2(\sigma_1R_1^2+\sigma_2R_2^2)B^2}, \quad (1)$$

$$R=\frac{\sigma_1^2R_1+\sigma_2^2R_2+\sigma_1^2\sigma_2^2R_1R_2(R_1+R_2)B^2}{(\sigma_1+\sigma_2)^2+\sigma_1^2\sigma_2^2(R_1+R_2)^2B^2}. \quad (2)$$

These equations apply to the sheet conductances $\sigma_{1\square}$ and $\sigma_{2\square}$ and sheet Hall coefficients $R_{1\square}$ and $R_{2\square}$ but we will leave off the "□" symbol. They also apply to two layers as well as two bands under the provisions discussed earlier.[12] For degenerate carriers, the Hall r factors are unity,[13] and thus $R_1=1/en_1$, $R_2=1/en_2$; also, $\sigma_1=en_1\mu_1$

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and $\sigma_2=en_2\mu_2$. By convention, R is usually considered to be negative for electrons and positive for holes; however, since we will mainly be dealing with electrons in our MODFET structures, we will reverse this convention. Then, if one of the layers is p type, its μ and n will turn out to be negative values.

There are four unknowns, μ_1, μ_2, n_1, and n_2, so that four equations are necessary for a solution. We first recast Eqs. (1) and (2) as follows:

$$\frac{1}{B^2}=S_\rho\frac{\rho_0}{\Delta\rho}-Y, \tag{3}$$

$$\frac{1}{B^2}=-S_R\frac{R_0}{\Delta R}-Y, \tag{4}$$

where $\rho=1/\sigma$, $\rho_0=\rho(B=0)$, $R_0=R(B=0)$, $\Delta\rho=\rho(B)-\rho_0$, $\Delta R=R(B)-R_0$, and

$$\sigma_0=\sigma_1+\sigma_2, \tag{5}$$

$$R_0=\frac{\sigma_1^2R_1+\sigma_2^2R_2}{(\sigma_1+\sigma_2)^2}, \tag{6}$$

$$S_\rho=\frac{\sigma_1\sigma_2(\sigma_1R_1-\sigma_2R_2)^2}{(\sigma_1+\sigma_2)^2}, \tag{7}$$

$$S_R=\frac{\sigma_1^2\sigma_2^2(R_1+R_2)(R_1\sigma_1-R_2\sigma_2)^2}{(\sigma_1+\sigma_2)^2(\sigma_1^2R_1+\sigma_2^2R_2)}. \tag{8}$$

We first note, as expected, that S_ρ and S_R vanish (no magnetic-field dependence) for the single layer case, i.e., if either σ_1 or $\sigma_2=0$. Secondly, we note that S_ρ is always positive for any R_1 and R_2, and S_R is positive if R_1 and R_2 have the same sign. Thus, within this formalism, ρ will always increase with B, and R will always decrease [note "$-S_R$" in Eq. (4)] with B if both the carriers are electrons or both holes. If the carriers are of opposite type, then R may either increase or decrease with B, depending on the relative sizes of σ_1, σ_2, R_1, and R_2.

We now invert Eqs. (5)–(8) to obtain an exact solution of μ_1, μ_2, n_1, and n_2 in terms of the four measurable parameters σ_0 (or ρ_0), R_0, S_ρ, and S_R. We define[14] $\beta=S_\rho/S_R$, $T=(R_0\sigma_0)^2/S_\rho$, $A=(2+T+T/\beta^2)/(1-T/\beta)$, $b=(-A+\sqrt{A^2-4})/2$, and $c=(\beta-b^{-1})/(b-\beta)$. Then

$$\mu_2=R_0\sigma_0\frac{1+bc}{1+b^2c},\quad \mu_1=b\mu_2, \tag{9}$$

$$n_2=\frac{1}{eR_0}\frac{1+b^2c}{(1+bc)^2},\quad n_1=cn_2, \tag{10}$$

$$\sigma_2=\sigma_0\frac{1}{1+bc},\quad \sigma_1=\sigma_0\frac{bc}{1+bc}. \tag{11}$$

It is possible to obtain the values of S_ρ and S_R from Eqs. (3) and (4) with only two values of magnetic field. However, in practice, we have found it convenient to use values B=0, 0.2, 1.0, and 1.6 T to determine S_ρ, and B=0.2, 1.0, and 1.6 T to determine S_R. Since $R\propto B^2$ at low B, we first plot $R(B)$ vs B^2 and get R_0 from the intercept. We then

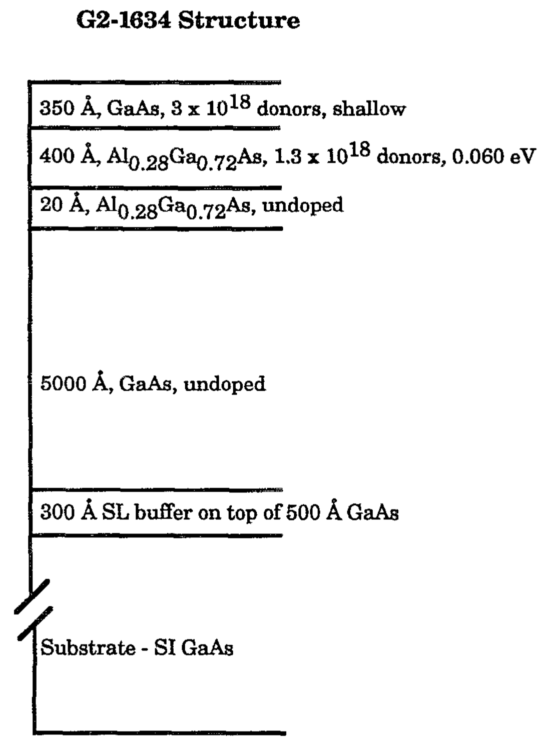

FIG. 1. A schematic diagram, not drawn to scale, of the MODFET structure.

carry out a least-squares fit of $1/B^2$ vs $\rho_0/\Delta\rho$ to get the slope S_ρ, and of $1/B^2$ vs $R_0/\Delta R$ to get the slope $-S_R$. In general, the $\rho_0/\Delta\rho$ plot is somewhat better than the $R_0/\Delta R$ plot, so that we use the intercept Y in the former [Eq. (3)] as an input point in the latter [Eq. (4)]. The entire analysis is carried out by using a simple GW BASIC computer program.

RESULTS

The basic MODFET material (sample 1634) investigated in this study, schematically illustrated in Fig. 1, is a standard device structure used in our laboratory and differing little from those used by others. A strong B dependence in ρ and R was found, as illustrated in Table I; thus a two-layer or possibly a three-layer analysis is suggested. To more fully characterize the n^+-GaAs and n^+-AlGaAs

TABLE I. Magnetic-field dependences of the measured sheet resistivity ρ and sheet Hall coefficient R at 77 K.

Sample	Structure	$\frac{\rho(1.6T)-\rho(0)}{\rho(0)}$	$\frac{R(1.6T)-R(0)}{R(0)}$
1634	MODFET: n^+ cap	2.76	−0.723
1635	MODFET: undoped cap	0.045	0.012
1636	1 μm, n^+-$Al_{0.3}Ga_{0.7}As$	−0.023	−0.017
1637	3 μm, n^+-GaAs	0	−0.0006
1652	MODFET: n^+ cap separated by 200 Å	0.125	0.018
1653	MODFET: n^+ cap separated by 400 Å	0.074	0.056

materials, we grew thick layers of each (samples 1637 and 1636, respectively). The n^+-GaAs electron concentration was shown to be about 3×10^{18} cm^{-3}, by both Hall-effect and Polaron C-V measurements, and the B dependence was very small, as expected. The n^+-AlGaAs had a Polaron C-V concentration of about 1.3×10^{18} cm^{-3}, but a Hall-effect concentration of only 2×10^{17} cm^{-3}, at 296 K. The reason for the difference here is that the Hall-effect experiment measures the free-electron concentration, and the low-frequency C-V experiment measures the total (or net) donor concentration. Since the donor DX centers[15] are about 60 meV deep in $Al_{0.3}Ga_{0.7}As$, it follows that $n \ll N_D$. At 77 K, $n \simeq 3\times10^{15}$ cm^{-3}, so that the n^+-AlGaAs is about a factor 15 less conductive than the n^+-GaAs cap at 296 K and 1000 less at 77 K, even ignoring electron transfer. With electron transfer to the GaAs cap, as well as to the GaAs channel layer underneath, the direct AlGaAs contribution to conduction is even less. Thus, our structure is really only a two-layer structure: the two-dimensional electron gas (2DEG) layer and the n^+-GaAs cap layer.

To confirm that the direct AlGaAs conductance is small, we grew a sample (1635) with an undoped GaAs cap, and the B dependences (Table I) of both ρ and R were a factor 60 below those of sample 1634. Thus, sample 1635 has only a single conductive layer, the 2DEG. In this case, the electrons from the AlGaAs which would normally spill over into the GaAs cap are lost to surface and interface states. (Note that the inverted interface, i.e., GaAs on top of AlGaAs, is known to be of poor quality.) We also grew MODFET structures with n^+-GaAs caps separated from the doped AlGaAs layers by 200-Å and 400-Å undoped AlGaAs layers, designated samples 1652 and 1653, respectively. The B dependences were also small for both of these samples, showing that the GaAs cap and AlGaAs conductances were not significant compared with that of the 2DEG. Thus, for these two samples, all of the cap electrons are evidently lost to surface and interface states. The total sheet donor charge in the cap is 1.05×10^{13} cm^{-2}, and we can calculate[13] that 5.5×10^{12} cm^{-2} would be lost to the usual surface states, which pin E_F at $E_C-0.7$ eV. Therefore, if E_F for the inverted interface were pinned at $E_C-0.64$ eV or lower, a reasonable assumption, all of the electrons would be immobilized, as observed.

It is thus interesting that the parallel conductance in the original MODFET structure, sample 1634, evidently does not arise solely from the electrons which come from the GaAs cap, but also from the electrons which spill over to the cap from the n^+-AlGaAs layer. Thus, the parallel conductance is in large part due to electrons which are *from* the AlGaAs but not *in* the AlGaAs.

CALCULATIONS AND DISCUSSION

The values of R and ρ were measured for samples 1634 and 1635 at 296 and 77 K in magnetic fields $B=0$, 0.2, 1.0, and 1.6 T. In actuality, the lowest controllable field with our magnet is about 0.025 T so that R_0 and ρ_0 were obtained by extrapolating the low-field values of R and ρ to $B=0$. Then, values of $\rho_0/\Delta\rho$ and $R_0/\Delta R$ were calculated at 0.2, 1.0, and 1.6 T and fitted to Eqs. (3) and (4) to get S_ρ and S_R, respectively. Other combinations of field values gave similar results as long as at least one of the three fields was low (0.2–0.4 T) and one high (> 1.0 T). All extrapolations and fits were done on a computer by the least-squares method. The values of ρ_0, R_0, S_ρ, and S_R were then used to calculate β, T, A, b, and c, and finally ρ_1, ρ_2, μ_1, μ_2, n_1, and n_2 from Eqs. (7)–(9), where layer 1 is the 2DEG and layer 2, the cap. The results are displayed in Table II.

TABLE II. Raw and fitted values of ρ, μ, and n for samples 1634 and 1635 at 296 and 77 K.

Sample	T (K)	Layer	ρ ($\Omega/\square$)	μ (cm^2/V s)	n (cm^{-2})
1634	296	both	5.99×10^2	4.77×10^3	2.18×10^{12}
		2DEG	1.05×10^3	7.61×10^3	7.78×10^{11}
		cap	1.39×10^3	1.04×10^3	4.34×10^{12}
	77	both	1.32×10^2	4.98×10^4	9.83×10^{11}
		2DEG	1.51×10^2	5.49×10^4	7.50×10^{11}
		cap	1.04×10^3	a	a
1635	296	both	9.84×10^2	6.66×10^3	9.52×10^{11}
		2DEG	9.95×10^2	6.72×10^3	9.33×10^{11}
		cap	9.00×10^4	a	a
	77	both	1.69×10^2	4.87×10^4	7.59×10^{11}
		2DEG	1.69×10^2	4.88×10^4	7.56×10^{11}
		cap	7.11×10^4	a	a

[a]Very inaccurate, because $\rho_{cap} \gg \rho_{2DEG}$.

The first and most important thing to note is that the 296 K values of ρ, μ, and n for sample 1634 are greatly influenced by the cap because the cap conductance is only slightly lower than that of the 2DEG. For example, the uncorrected 296-K mobility value, 4770 cm^2/V s, would denote relatively poor material, whereas the corrected value of 7610 cm^2/V s is indicative of good material. Similarly, the uncorrected 296-K carrier concentration of 2.18×10^{12} cm^{-2} is much too high, and would greatly distort any device modeling based on that number. However, at 77 K, the 2DEG conductance has increased greatly because of the much higher μ, whereas the cap conductance has changed very little, as expected for the degenerate cap material. Thus, the 2DEG region dominates the electrical properties at 77 K, although the correction to n is still significant. Because of the low relative cap conductance, it is difficult to get good separate values of μ_{cap} and n_{cap} at 77 K for MODFETs, although ρ_{cap} should still be fairly accurate, in our experience. Note also that the corrected 296 and 77 K values of n are nearly the same, as they should be, whereas the uncorrected 296-K value is much higher. This is the reason that the usual (uncorrected) n vs T plots for MODFET material nearly always increase rapidly as room temperature is approached.[16] The increase is not, as often stated, due to donor ionization, but is more likely due to the two-layer phenomenon discussed here. In fact, if there is a GaAs cap, the electrons which would have ionized in the AlGaAs will mostly have transferred to the cap at both 77 and 296 K, so that the parallel conductance will remain relatively independent of temperature. This is the case for sample 1634, in which ρ_{cap} changes little between 296 and 77 K.

For sample 1635, containing an *undoped* cap, the uncorrected and corrected 2DEG values of ρ, μ, and n are nearly the same, because $\rho_{cap} \gg \rho_{2DEG}$. However, this fact would not have been known without a magnetic-field analysis, or without at least one measurement of ρ and R at higher field. Thus, it seems profitable to routinely carry out a high-field measurement of ρ and R in MODFET structures to go with the usual low-field measurement. Then, if a field dependence is seen, further measurements at one or two other fields can be taken and the analysis presented here applied.

In summary, we have presented an exact solution of the magnetic-field-dependent Hall and conductivity equations and applied it to MODFET structures at 296 and 77 K. It is shown that "parallel conduction" in the n^+-GaAs cap layer greatly distorts the 2DEG mobility and carrier concentration at 296 K, and less significantly at 77 K. The conductance in the n^+-GaAs cap involves electrons which transfer from the AlGaAs as well as electrons which are in the cap to begin with.

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