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Review of Hall Effect and Magnetoresistance Measurements in GaAs Materials and Devices

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ABSTRACT

The use of magnetic fields in the electrical characterization of semiconductor materials is familiar to everyone in the form of Hall-effect measurements. However, there is another magnetic-field-based phenomenon, magnetoresistance (MR), which is highly useful but not nearly so familiar to the majority of workers. One of the unique features of MR measurements is their applicability to common device structures, in particular, field-effect transistors (FETs) and contact-resistance patterns. We will show how channel mobility information can be extracted from the MR data in metal-semiconductor FETs (MESFETs) and modulation-doped heterostructure FETs (MODFETs), and also how the material under ohmic contacts can be compared with the unprocessed material to see if appreciable contact-element diffusion has occurred. Finally, we will consider some common problems which are often overlooked in performing simple Hall-effect measurements on thin structures. Some useful formulas and plots are presented.

Magnetic fields have been a part of metal and semiconductor characterization for many years, at least since 1879 when E. H. Hall made his famous discovery of what we now know as the "Hall effect" (1). In what must be regarded as a classic understatement, Hall suggested that "a more complete and accurate study of the phenomenon will probably occupy me for some months to come." Indeed, it has occupied the time of a great number of researchers since then and thus would seemingly be too familiar and mundane a topic to be worthwhile for this symposium. However, there are many aspects of the Hall effect which are not as familiar to the general worker, and yet can be very important for characterization purposes. We will briefly discuss several of these and will also present some useful figures and further references. Because so much emphasis is being placed on thin-layer structures these days, we will concentrate on the particular measurement problems associated with thin layers.

Besides the Hall effect, however, several more recent developments involving magnetoresistance in device structures have proven to be of use in semiconductor characterization. The major virtue of these new techniques is that they can give materials parameters in actual device structures. In particular, we will discuss magnetoresistance in MESFETs, MODFETs, and contact-resistance transmission-line-model (TLM) patterns. Our prime examples will be GaAs and AlGaAs/GaAs, since much of the recent magnetoresistance work has involved these materials, and also since the present author is most familiar with these particular materials.

The Hall Effect: Experiments in Bulk Materials

When a system of electrons in equilibrium is perturbed by the application of electric and magnetic fields, collisional forces will attempt to restore the system to equilibrium. For many types of such collisions, this restoration will be exponential in nature with a characteristic time constant τ , the "relaxation time." Then, in simple isotropic systems, the current densities set up by the fields will be given by

$$j_x = \sigma_{xx}E_x + \sigma_{xy}E_y \quad [1]$$

$$j_y = \sigma_{yx}E_x + \sigma_{yy}E_y \quad [2]$$

where E_x and E_y are the electric field components, and, for an n-type sample

$$\sigma_{xx} = \sigma_{yy} = \frac{ne^2}{m^*} \left\langle \frac{\tau}{1 + \omega_c^2 \tau^2} \right\rangle \quad [3]$$

$$\sigma_{xy} = -\sigma_{yx} = -\frac{ne^2}{m^*} \left\langle \frac{\omega_c \tau^2}{1 + \omega_c^2 \tau^2} \right\rangle \quad [4]$$

where $\omega_c = eB/m^*$ is the cyclotron frequency and the other symbols have their usual meanings. The brackets denote an average over electron energy ϵ defined by

$$\langle f(\tau) \rangle = \frac{\int_0^\infty f(\tau) \epsilon^{3/2} \frac{\partial f_0}{\partial \epsilon} d\epsilon}{\int_0^\infty \epsilon^{3/2} \frac{\partial f_0}{\partial \epsilon} d\epsilon} \quad [5]$$

where f_0 is the equilibrium Fermi function. We can now define the quantities of interest for this paper: the Hall coefficient, R_H , the Hall mobility, μ_H , and the geometric magnetoresistance (GMR) mobility, μ_{GMR} .

The Hall coefficient is measured in a prototype structure such as that shown in Fig. 1a, the "Hall bar." This structure is long and narrow, and the voltage contacts, to measure V_c and V_H , are placed far from the large-area current contacts on the ends of the sample in order to avoid voltage shorting by the current contacts. Because the voltage contacts do not carry current, $J_y = 0$. The Hall coefficient is then defined as

$$R_H \equiv \frac{E_y}{j_x B} \bigg|_{j_y=0} = \frac{1}{B} \frac{\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2} \quad [6]$$

At $B = 0$

$$R_H = -\frac{1}{ne} \frac{\langle \tau^2 \rangle}{\langle \tau \rangle^2} \equiv -\frac{r}{ne} \equiv -\frac{1}{n_H e} \quad [7]$$

where r is the "Hall factor" and n_H is the "Hall concentration," the concentration actually measured in a Hall experiment. The quantity r usually must be calculated by fitting

Fig. 1. (a) A standard Hall-bar configuration. (b) A geometric-magnetoresistance configuration.

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Fig. 2. The Hall r -factor at 77 K as a function of carrier concentration n for two different compensation ratios. Here, N_i is the ionized-impurity concentration.

μ_H vs. T to a theoretical scattering formula made up of all contributions to the scattering. If inelastic scattering is important, as is the case in GaAs at room temperature, then $r \neq \langle \tau^2 \rangle / \langle \tau \rangle^2$, and numerical solutions of the Boltzmann equation must be carried out to get r . The results of one such calculation are shown in Fig. 2 for various values of n_H and ionized-impurity concentration N_i , at $T = 77$ K, an important characterization temperature. As is seen, the relationship $r = 1.2 \pm 0.2$ encompasses nearly all GaAs material at this temperature.

To determine the Hall mobility μ_H , we must also perform a conductivity experiment

$$j_x \bigg|_{\substack{j_y=0 \\ B=0}} = \frac{\sigma_{xx}^2 + \sigma_{xy}^2}{\sigma_{xx}} E_x \bigg|_{B=0} = \sigma_{xx} E_x = \frac{ne^2 \langle \tau \rangle}{m^*} E_x = ne\mu E_x \quad [8]$$

where $\mu = e\langle \tau \rangle / m^*$ is known as the "conductivity mobility." The Hall mobility is now defined as

$$\mu_H \equiv R_H \sigma = -\frac{r}{ne} ne\mu = -r\mu \quad [9]$$

With respect to the symbols in Fig. 1a, we calculate n_H and μ_H , along with the resistivity ρ , in laboratory units as

$$\rho = \frac{wd}{\ell} \frac{V_c}{I} \quad [10]$$

$$\mu_H = \frac{10^8}{B(\text{gauss})} \frac{V_H}{V_c} \frac{\ell \text{ cm}^2}{w \text{ V-s}} \quad [11]$$

$$n_H = 6.25 \times 10^{10} \frac{I(\text{amp}) B(\text{gauss})}{V_H(\text{volts}) d(\text{cm})} \text{ cm}^{-3} \quad [12]$$

where d is the sample thickness. Equations [11] and [12] are strictly true only for $[\mu(\text{m}^2/\text{V-s}) B(T)]^2 \ll 1$ or $[\mu(\text{cm}^2/\text{V-s}) B(\text{G})]^2 \ll 10^{16}$, if the electrons are nondegenerate. Typically, $B \approx 5 \times 10^3 \text{ G}$, so that low- B conditions are applicable as long as $\mu \leq 2 \times 10^4 \text{ cm}^2/\text{V-s}$. Even for higher values of μB , Eq. [11] and [12] are often a good approximation.

However, rather than a Hall-bar structure, it is probably more common to use one of the "van der Pauw" configurations (2), shown in Fig. 3. In this case, it is necessary to permute current (i, j) and voltage (k, l) leads in order to calculate ρ , μ_H , and n_H as follows

$$\rho = \frac{\pi d}{\ell n 2} \left[\frac{R_{21,34} + R_{32,41}}{2} \right] f \quad [13]$$

$$R_H = \frac{d}{B} \left[\frac{R_{31,42} + R_{42,13}}{2} \right] \quad [14]$$

where $R_{ij,kl} \equiv V_{kl}/I_{ij}$, and f is a factor due to shape asymmetry. However, for all the structures in Fig. 3, which are symmetric, f should equal unity; if it does not, the material is probably inhomogeneous. In order to average out some of the spurious emfs which can influence V_H , it is good to average over current and magnetic field polarities.

There are advantages and disadvantages to the various Hall-bar and van der Pauw configurations shown in Fig. 3. For example, contact-size effects are less important in (b) and (d) than in (a) and (c); however, (a) is obviously the easiest to fabricate. Considerations such as these are discussed in detail in the books by Wieder (3) and Look (4).

Hall measurements in thin films.—It is of interest to mention here two effects which can be important in thin-film Hall measurements but are often ignored. The first is current shunting due to substrate conduction. Suppose the substrate is 10^3 times as thick as the conductive layer it supports; then, for the substrate to conduct less than 1% of the total current, it must have a resistivity at least 10^5 times that of the layer. This effect can be quantified as follows (5)

$$\rho^{-1} = \sigma = \frac{\sigma_s d_s + \sigma_\ell d_\ell}{d_s + d_\ell} = \frac{d_s/\rho_s + d_\ell/\rho_\ell}{d_s + d_\ell} \quad [15]$$

$$\mu_H = |R_H \sigma| = \left| \frac{R_{Hs} \sigma_\ell^2 d_\ell + R_{H\ell} \sigma_s^2 d_s}{\sigma_\ell d_\ell + \sigma_s d_s} \right| \quad [16]$$

where the subscripts s and ℓ refer to the substrate and layer, respectively. As an example, suppose we are measuring a pure, p-type GaAs layer on an n-type, semi-insulating (SI) substrate; then

$$\mu_H = \left| \frac{p_\ell \mu_{p\ell}^2 d_\ell - n_s \mu_{ns}^2 d_s}{p_\ell \mu_{p\ell} d_\ell + n_s \mu_{ns} d_s} \right| \quad [17]$$

The typical numbers might be: $n_s \approx 10^{17} \text{ cm}^{-3}$, $p_\ell \approx 10^{13} \text{ cm}^{-3}$, $\mu_{ns} \approx 8 \times 10^3 \text{ cm}^2/\text{V-s}$, $\mu_{p\ell} \approx 4 \times 10^2 \text{ cm}^2/\text{V-s}$, and $d_s \approx 500 \mu\text{m}$. Then, unless $d_\ell > 0.2 \mu\text{m}$, the layer will "appear" to be n-type rather than p-type. Even at $d_\ell \approx 2 \mu\text{m}$, the measured mobility will be significantly lowered because of the n-type contribution to R_H from the substrate. If depletion effects (see below) are considered, the effective d_ℓ is even

Fig. 3. Four common patterns used for van der Pauw resistivity and Hall-effect: (a) square, (b) Greek cross, (c) circle, and (d) cloverleaf.

lower. At higher temperatures, the effect will also be more severe, since n increases rapidly in SI GaAs. These same problems occur in Si, and are potentially worse, since Si does not have a semi-insulating form to give as good a substrate.

Another problem in thin structures is surface and interface depletion (6). Consider the band diagram shown in Fig. 4, for an n-type layer on SI GaAs. The regions in which the bands bend upward are depleted of free electrons and thus carry no current. (In Fig. 4 it is assumed the free carriers depleted from near the interface are all accommodated at interface states, not substrate states. This assumption is often true, but not always.) The "electrical thickness," which is the thickness to be used in the R_H and σ formulas, is given by

$$d_{\text{eff}} = d_t - w_s - w_i = d_t - \left[\frac{2\epsilon}{e(N_D - N_A)} \right]^{1/2} \left[\left(\phi_{\text{sn}} - \phi_t - \frac{kT}{e} \right)^{1/2} + \left(\phi_{\text{si}} - \phi_t - \frac{kT}{e} \right)^{1/2} \right] \quad [18]$$

where ϵ is the static dielectric constants (1.1431×10^{-10} F/m in GaAs), N_D and N_A are the donor and acceptor concentrations, respectively, and the various potentials are defined in Fig. 4. Analytical expressions can be given for ϕ_{sn} , ϕ_t , and ϕ_{si} , but it is perhaps more useful to show plots of $w = w_s + w_i$, which are presented in Fig. 5 for GaAs. Note that a $1 \mu\text{m}$ layer of 10^{15} cm^{-3} GaAs would not conduct any current at all ($w_s + w_i > d_t$). Even a typical $0.1 \mu\text{m}$ FET layer, with $n = 2 \times 10^{17} \text{ cm}^{-3}$, must be corrected for depletion to get the proper values of n and ρ . Fortunately, however, μ is independent of thickness and will not be affected.

Temperature dependence.—So far, we have barely scratched the surface of what is available with the Hall-effect technique. Beyond being a useful general characterization tool, it is also one of the best ways to get reliable activation energies (more so than DLTS, which can have interference from the capture cross-sectional energy dependence) and one of the only ways to get donor and acceptor concentrations. The procedure for doing this, with maximum accuracy, first involves finding the Hall-factor r , as follows:

1. Measure R_H and σ vs. T .
 2. Initially, let $r = 1$ for all T ; i.e., $n_{(1)} = (eR_H)^{-1}$.
 3. Let $\mu_{(1)} = \mu_H = |R\sigma|$. Then fit μ to the total theoretical scattering expression by an appropriate numerical technique. For the free-carrier screening terms, especially in the ionized-impurity scattering formula, let $n = n_{(1)}$. Determine the ionized-impurity concentration N_I , and perhaps other undetermined constants, by the fit.
 4. With the various scattering strengths now known, to first order, compute $r_{(1)}$, either by the formula $r = \langle \tau^2 \rangle / \langle \tau \rangle^2$, or by a more sophisticated numerical technique if required.
 5. Now let $n_{(2)} = r_{(1)} / eR_H$, $\mu_{(2)} = \mu_H / r_{(1)}$, and find a new N_I by the mobility fit.
 6. Go to step 4, find a new r [i.e., $r_{(2)}$], etc. Usually, no more than two to three iterations are necessary.
- Once the r 's are found for each temperature, then the true n 's can be calculated and the charge-balance equation

Fig. 4. Conduction-band energy diagram showing surface and interface depletion effects. The effective electrical thickness is given by d_{eff} .

Fig. 5. Total depletion width $w = w_s + w_i$ as a function of carrier concentration n at 77 and 296 K.

may be fitted. For nondegenerate, n-type material the appropriate equation is

$$n + N_A^{\text{net}} = \frac{N_D}{1 + \left[\frac{g_1}{g_0} \frac{1}{N_c} e^{-\alpha/k} \right] e^{E_{D0}/kT} \frac{n}{T^{3/2}}} \quad [19]$$

where g_1 and g_0 are the occupied and unoccupied state degeneracies, respectively, $N_c = 2(2\pi m^* k)^{3/2} / h^3$, $E_D = (E_{D0} - \alpha T)$ is the donor activation energy (α is the temperature coefficient), and $N_A^{\text{net}} = N_A$ (below E_F) - N_D (above E_F). The fitting parameters are N_D , N_A^{net} , E_{D0} , and $N_c(g_0/g_1) \exp(\alpha/k)$. For thin layers, the effective electrical thicknesses should be calculated by means of Fig. 5 or Eq. [18]; otherwise, the data at higher temperatures may be distorted (7).

Geometric Magnetoresistance: Experiments on Devices

Hall-effect experiments demand a long, narrow sample as shown in Fig. 1a. A sample with an opposite aspect ratio is shown in Fig. 1b, and it is clear that as the length $\ell \rightarrow 0$ the Hall field E_y will be shorted out by the current contacts, i.e., $E_y \rightarrow 0$. Then Eq. [1] reduces to a particularly simple form

$$j_x \Big|_{E_y=0} = \sigma_{xx} E_x = \frac{ne^2}{m^*} \left\langle \frac{\tau}{1 + \omega_c^2 \tau^2} \right\rangle E_x \quad [20]$$

and for $\omega_c^2 \tau^2 \ll 1$ (or $[\mu(m^2/V\text{-s})B(T)]^2 \ll 1$)

$$j_x \Big|_{E_y=0} = \frac{ne^2}{m^*} [\langle \tau \rangle - \omega_c^2 \langle \tau^3 \rangle] = ne\mu [1 - \xi_{\text{GMR}} \mu^2 B^2] E_x = ne\mu [1 - \mu_{\text{GMR}}^2 B^2] E_x \quad [21]$$

where $\mu = e\tau/m^*$ is just the familiar conductivity mobility, and $\xi_{\text{GMR}} = \langle \tau^3 \rangle / \langle \tau \rangle^3$ is the geometric magnetoresistance coefficient. Usually, we measure the conductance $G \equiv I_x/V_x = (wd/\ell)\sigma$. Then, from Eq. [21], we calculate a very simple and useful relationship (8)

$$\mu_{\text{GMR}} = \frac{1}{B(\text{MKS})} \left[\frac{G_0}{G_B} - 1 \right]^{1/2} = \frac{10^8}{B(\text{gauss})} \left[\frac{G_0}{G_B} - 1 \right]^{1/2} \quad [22]$$

where $G_0 \equiv G(B=0)$. For degenerate electrons, Eq. [22] holds exactly for arbitrary μB , as long as quantum effects are negligible; also, in that case, $\xi_{\text{GMR}} = 1$, so $\mu_{\text{GMR}} = \mu$. For an FET, the electrons are nearly always degenerate, except near pinch-off.

Mobility under an ohmic contact.—A commonly used pattern for measuring the resistance of planar contacts is shown in Fig. 6. It is clear that the total resistance between two contacts separated by ℓ_i is

$$R = 2R_c + r_s \frac{\ell_i}{w} \quad [23]$$

Fig. 6. (a) A common test pattern (the "TLM" pattern) for contact-resistance measurements. (b) A schematic diagram of the expected total resistance R as a function of contact spacing ℓ_i . Here, R_c is the contact resistance and r_s is the sheet resistance of the material between the contacts.

where R_c is the resistance due to one of the contacts and r_s is the sheet resistance of the bulk material between the contacts. (The subscript s will denote a sheet resistance or sheet carrier concentration.) To find the sheet resistance R_s of the material under a contact requires an "end-resistance" measurement (9) which involves a third contact and is often difficult to carry out accurately. By treating the region under the contact as a transmission line, it can be shown that (10)

$$R_c = \frac{\sqrt{R_s \rho_c}}{w} \cosh k\ell_c \xrightarrow{k\ell_c \gg 1} \frac{\sqrt{R_s \rho_c}}{w} \quad [24]$$

where $k^2 = R_s/\rho_c$, and ρ_c is the specific contact resistivity of the metal/semiconductor (M/S) barrier. Equation [24] involves the sheet resistance R_s , not r_s , because the current must flow under part of the contact after passing through the M/S barrier. However, unless we know R_s we cannot calculate ρ_c .

To get further information, we can apply a magnetic field. Note that each pair of contacts in Fig. 6 appears to have a GMR configuration, as shown in Fig. 1a, as long as $w/\ell_i \gg 1$. In that case, the field increases each sheet resistance according to the relationship $R(B) = R(0)[1 + \mu_{\text{GMR}}^2 B^2]$. Since normally $\xi \approx 1$, we will assume that $\mu_{\text{GMR}} = \mu$ for purposes of this discussion. Then, Eq. [23] and [24] lead to (11)

$$\begin{aligned} R(B) &= 2R_c(B) + \frac{\ell_i}{w} r_s(B) \\ &= 2R_{c0} (1 + \mu_c^2 B^2)^{1/2} + \frac{\ell_i}{w} r_{s0} (1 + \mu^2 B^2) \end{aligned} \quad [25]$$

where μ_c and μ are, respectively, the mobilities of the material under the contacts and between the contacts, and the subscript 0 denotes a measurement at $B = 0$. Note that $R_c(B)$ and $r_s(B)$ can be found in the usual way, as illustrated in Fig. 6b, and then μ_c can be determined from $R_c^2(B)$ vs. B^2 , and μ from $r_s(B)$. If μ_c is much different than μ , then it is obvious that the contact fabrication process has affected the material under the contact.

To illustrate these ideas, we show R vs. ℓ_i data (Fig. 7a), and R_c^2 and r_s vs. B^2 data (Fig. 7b) for an ion-implanted

Fig. 7. (a) Actual plots of R vs. ℓ_i (cf. Fig. 6) for GaAs MESFET material at three different magnetic fields, B . The bottom part of the figure is an expanded version of the region near the origin. Reproduced by permission of the IEEE. (b) The sheet resistance r_s and the contact resistance squared R_c^2 vs. B^2 in GaAs MESFET material. These data were obtained from the slopes and intercepts of the lines in Fig. 7a as well as from data at two other magnetic fields, not shown in Fig. 7a to avoid clutter. Reproduced by permission of the IEEE.

GaAs MESFET (11). The straight lines show that the various relationships all hold quite well and that the calculated parameters, shown below, are therefore probably accurate: $r_c = R_c w = 0.29 \Omega\text{-mm}$; $\rho_c = 6.3 \times 10^{-7} \Omega\text{-cm}^2$; $r_{s0} = 1.4 \times 10^3 \Omega/\square$; $\mu = 4.3 \times 10^3 \text{ cm}^2/\text{V-s}$; $\mu_c = 4.3 \times 10^3 \text{ cm}^2/\text{V-s}$. Thus, $\mu_c \approx \mu$ in this case, and therefore contact-element diffusion has evidently not greatly affected the material under the contact. Then we can assume $R_s \approx r_s$ and calculate ρ_c from Eq. [24].

Actually, the TLM test pattern, Fig. 6a, is quite useful in its own right outside of contact-resistance studies, because it substitutes for a Hall-effect measurement. That is, we get r_{s0} and μ from the analysis so that the sheet carrier concentration n_s can easily be calculated from $n_s = \ell_i / e\mu r_{s0} w = 1.1 \times 10^{12} \text{ cm}^{-2}$ in the above example. Just as the Hall-effect measurement eliminates parasitic resistance effects by measuring voltages at contacts which carry no current, so the magneto-TLM measurements eliminate parasitic resistance effects by measuring voltages at more than one pair of contacts. Note that the Hall effect is still better for low mobilities, because it is first-order in μB , whereas the GMR effect is second-order.

Finally, we should mention the effects of not having a perfect GMR condition, $\ell/w \rightarrow 0$. Kuhrt and Lippmann (12)

have shown that, for μB and $\ell/w \lesssim 0.4$, the resistance can be written

$$R(B) = R(0) [1 + \mu^2 B^2 (1 - 0.54\ell/w)] \quad [26]$$

Thus, if $\ell/w \lesssim 0.2$, an easily attainable condition, the correction to μ is less than 6%.

Mobility profiles in FET structures.—By applying a Schottky-barrier gate to a semiconductor surface, the depletion width w_d under the surface can be controlled by the voltage V_G on the gate. If $e\phi_B$ is the M/S barrier energy, then w_d is given in the depletion approximation by

$$w_d = \left[\frac{2\epsilon(V_{bi} - V_G - kT/e)}{e(N_D - N_A)} \right]^{1/2} \quad [27]$$

In Fig. 8, the values of w_d are shown for two different values of V_G . Now it can be shown that Eq. [22], which gives only an average value of μ , can be modified to give the value of μ at w_d . The relevant equation (13) is

$$\mu[w_d(V_G)] = \frac{1}{B} \left[\frac{\Delta G_0(V_G)}{\Delta G_B(V_G)} - 1 \right]^{1/2} \quad [28]$$

where $\Delta G \equiv G(V_G + \Delta V_G) - G(V_G)$. Thus, by varying V_G in steps of ΔV_G , it is possible to profile μ through the layer. For highly conductive layers, unfortunately, it is impossible to profile over large distances, because the Schottky diode breaks down. However, for typical GaAs MESFET layers of $n \approx 2 \times 10^{17} \text{ cm}^{-3}$ and $d = 0.1 - 0.2 \text{ }\mu\text{m}$, there is usually no problem.

One of the great advantages of the measurements described here is that they can be performed in actual FET structures, even short-gate ($\ell_G \lesssim 1 \text{ }\mu\text{m}$) structures. However, in these small structures it becomes difficult to accurately measure w_d , because that is usually done with a capacitance measurement

$$w_d = \frac{\epsilon A}{C} \quad [29]$$

where A is the effective gate area, not necessarily equal to the actual gate area for a small gate. Thus, a large-gate or "FATFET" device is better for the capacitance measurements.

A problem with mobility profiling in a MESFET is that we are dealing with a two-terminal structure and thus parasitic resistances can be important, especially under open-channel conditions. There are various ways to deal with this problem, but the cleanest way is to have two or more FETs of different gate lengths but identical in every other respect. A special test structure known as a gated-TLM pattern is shown in Fig. 9. Here the total parasitic resistance R_p between two contacts consists of the contact resistances and the access resistances. It is clear that

Fig. 8. The conduction-band energy diagrams for a metal/semiconductor interface at two different gate biases, 0 and V_G , where V_G is negative here. Note how the depletion width w_d increases as reverse bias is increased.

$$R_i(V_G) = R_p + \frac{\ell_{Gi}}{w} R_s(V_G) = R_p + R_{ch}(V_G) \quad [30]$$

where R_s is the sheet resistance of the undepleted material (between w_d and d) under the gate of length ℓ_{Gi} . By plotting R_i vs. ℓ_{Gi} at a given V_G , both R_p and $R_s(V_G)$ can be calculated. An example is given in Fig. 10 and it is seen that R_p is nearly constant, as it should be by definition. The true mobility profile, without parasitic-resistance effects, can now be calculated and is shown in Fig. 11 for this particular case.

A final problem is that of gate current, which is drawn at the high forward biases necessary to profile close to the surface (cf. Eq. [27]). This problem has also been dealt with (13) and the effects of the correction are shown in Fig. 11.

Magnetoelectric Experiments in Heterostructure Materials and Devices

Exactly the same kinds of experiments as discussed earlier can be performed on heterostructure materials and devices. However, the interpretations can be significantly different, mainly because (i) conduction can occur in several different bands and layers (ii) the energy levels and shapes of the bands themselves depend on the free-charge density, and (iii) quantum effects are also important. These phenomena are illustrated in Fig. 12 which shows the band diagram for modulation-doped AlGaAs/GaAs heterostructure material but would also apply to many other heterostructure pairs. The idea of modulation doping is that donors are placed in the high-bandgap material (AlGaAs), but the free electrons transfer to the low-bandgap material (GaAs) which has a higher electron affinity. Because the low-bandgap material is undoped and the parent donors are separated from the free electrons, the electron mobilities and saturation velocities can be very high. (Over $5 \times 10^6 \text{ cm}^2/\text{V}\cdot\text{s}$ has been achieved at 2 K (14).) Thus, fast FETs (MODFETs) can be designated.

The electrons transferring to the GaAs bend the bands down, and since a barrier already exists due to the conduction band discontinuity, a triangular well of approximate width δ is formed. The electrons in this well have two-dimensional character because they are bound in the z direction and will reside in subbands with energies E_0, E_1, E_2 , etc.; however, these energies, their concomitant wave functions, and the relative concentrations of electrons will depend on the total sheet electron concentration n_s and thus on the gate voltage V_G which controls n_s . From these considerations, it is clear that the charge-control problem (n_s vs. V_G) must be solved self-consistently, including a solution of Schrodinger's equation in the well region and a solution of Poisson's equation in both regions. Such calculations have been carried out by several groups and good analytical approximations are also available. However, the simple depletion approximation applicable to MESFETs is no longer valid, because the sample cannot be split into two regions, one completely devoid of electrons and the other having an equilibrium density of electrons (with only the position of the border between the two regions being affected by the gate voltage). Instead, the current parallel to the interface can be conducted in two different regions, the AlGaAs and GaAs, and in several different

Fig. 9. A "gated-TLM" test pattern. By taking resistance R readings between successive pairs of ohmic contacts at a given V_G and plotting R vs. ℓ_{Gi} , both the parasitic resistance R_p and sheet resistance R_s under the gate can be determined at the given V_G . By varying V_G , profiles of R , may be obtained.

Fig. 10. Actual R_{ch} and R_p vs. V_G data from GaAs MESFET material as determined from a gated TLM pattern. Here R_{ch} is the channel resistance of a $10 \times 100 \mu\text{m}$ gate MESFET. Reproduced by permission of The American Institute of Physics.

Fig. 11. The uncorrected and corrected (for gate current) mobility μ profiles in a $50 \times 400 \mu\text{m}$ gate GaAs MESFET, as measured by the GMR technique. Also shown is the carrier concentration n profile, as measured by C-V. Reproduced by permission of The American Institute of Physics.

bands in the GaAs. We therefore must include multiband and multilayer effects in the Hall-effect and GMR analyses.

Hall effect in heterostructures.—The volume electron concentrations, especially in the subband region, will be strong functions of position, and therefore it is much simpler to deal with the sheet electron concentrations n_{si} , where i denotes the relevant band. Of course, by doing this we are giving up any hope of “profiling,” either of carrier concentration or mobility. If z is the direction perpendicular to the surface, then the currents I_x and I_y can be written

$$I_x = w \left\{ E_x \sum_i \int_0^\infty \sigma_{xxi}(z) dz + E_y \sum_i \int_0^\infty \sigma_{xyi}(z) dz \right\}$$

$$= w \left\{ E_x \sum_i \frac{en_{si}\mu_i}{1 + \mu_i^2 B^2} - E_y \sum_i \frac{en_{si}\mu_i^2 B}{1 + \mu_i^2 B^2} \right\} \quad [31]$$

$$I_y = w \left\{ E_x \sum_i \frac{en_{si}\mu_i^2 B}{1 + \mu_i^2 B^2} + E_y \sum_i \frac{en_{si}\mu_i}{1 + \mu_i^2 B^2} \right\} \quad [32]$$

Fig. 12. The conduction-band energy diagram for an $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ MODFET with an undoped spacer of width d_s . Note how the ionized donors, denoted by “+”, are separated from the electrons in the GaAs subbands, denoted by “.”. The typical well dimension δ is about $80\text{\AA}$.

where it is assumed that E_x and E_y are constant and that the electrons are degenerate for simplicity. Then, the Hall mobility will be given by

$$\mu_H = \frac{E_y}{E_x B} \bigg|_{I_y=0} = \frac{\sum \frac{n_{si}\mu_i^2}{1 + \mu_i^2 B^2}}{\sum \frac{n_{si}\mu_i}{1 + \mu_i^2 B^2}} \xrightarrow{B \rightarrow 0} \frac{\sum n_{si}\mu_i^2}{\sum n_{si}\mu_i} \quad [33]$$

The conductance at $B = 0$, G_0 , is calculated from

$$G_0 = \frac{I_x}{V_x} \bigg|_{B=0} = \frac{w}{\ell} \frac{I_x}{E_x} \bigg|_{B=0} = \frac{w}{\ell} \sum en_{si}\mu_i \quad [34]$$

Even for two bands the number of unknowns is four, and more information is needed. Stormer *et al.* (15) used Shubnikov-de Haas oscillations to get n_0 and n_1 , and then could solve for μ_0 and μ_1 . Another way is to measure μ_H as a function B and then fit Eq. [33] with Eq. [34].

An important problem in heterostructure FETs is the existence of parallel conduction, *i.e.*, conduction from low-mobility electrons in the AlGaAs. This problem is especially acute in power devices for which the gate voltage is subject to large swings, even into the forward-bias region. Equations [33] and [34] are adequate to analyze this situation with one of the n_{si} 's denoting the sheet carrier concentration in the AlGaAs. However, there now exists a subtle complication, because at each voltage contact, currents will have to flow between the layers to maintain that contact at a single potential. This situation has been discussed by Syphers *et al.* (16).

TLM analysis in heterostructures.—The simple TLM expression (Eq. [24]) relating the contact resistance R_c to the specific contact resistivity ρ_c becomes much more complicated when there are two layers involved, because current mixing between the layers in them is possible, both in the region under the contacts and in the bulk region between the contacts. The two relevant layers in the heterostructure are the GaAs, next to the interface, and the neutral region in the AlGaAs. It has been shown that the use of the standard, single-layer model can lead to significant error in ρ_c in such cases (17, 18). Here the magnetic-field dependence can be quite valuable in determining the correct parameters (18). For example, in Fig. 13 is shown the μ vs. T curves for both the bulk region and the region under the contacts determined by a two-layer magneto-TLM analysis. The lower curve suggests that the material under the contact retains two-dimensional character, in spite of contact-element diffusion.

Geometric magnetoresistance in heterostructures.—To apply the GMR concepts in MODFET structures, we solve Eq. [31] and [32] under the boundary condition $E_y = 0$. Then

Fig. 13. The temperature dependences of the bulk mobility μ (between the contacts) and the mobility μ_c of the material in the well region under the contacts. Note that both regions show classical two-dimensional μ vs. T behavior. Reproduced by permission of The Electrochemical Society, Inc.

Fig. 14. The measured GMR-differential mobilities μ_D , at $B = 9$ and 18 kG, and the subband mobilities μ_0 and μ_1 , obtained by fitting the data.

it can be shown (4) that an "average" mobility can be defined in analogy to Eq. [22] as

$$\mu_A^2 = \frac{1}{B^2} \left[\frac{G_0}{G_B} - 1 \right] = \frac{\sum \frac{n_{si}\mu_i^3}{1 + \mu_i^2 B^2}}{\sum \frac{n_{si}\mu_i}{1 + \mu_i^2 B^2}} \quad [35]$$

and a "differential" mobility in analogy to Eq. [28] as

$$\mu_D^2 = \frac{1}{B^2} \left[\frac{\Delta G_0}{\Delta G_B} - 1 \right] = \frac{\sum C_i \frac{\mu_i^3}{1 + \mu_i^2 B^2}}{\sum C_i \frac{\mu_i}{1 + \mu_i^2 B^2}} \quad [36]$$

where C_i is the capacitance due to the i^{th} band, and it has been assumed that $d\mu_i/dV_G = 0$. Some results for μ_D vs. V_G and the fitted μ_0 and μ_1 are shown in Fig. 14. The curve for μ_0 is probably fairly accurate, because most of the electrons are in the lowest subband, while that for μ_1 is only rough.

Other uses of a magnetic field.—Two relatively recent innovations in magnetoelectric characterization include Hall-current profiling (19) and Hall-DLTS (20). The former makes use of the fact that, although the Hall electric field is shorted out in a FET-type structure, a Hall current I_y will exist and can be detected if either the source or drain is split, as is the case for some RF-designed devices. However, the Hall currents tend to be relatively small and at present it is unknown how useful this technique will be.

The Hall-DLTS technique (or Hall-effect transient spectroscopy) is based on the time constant of the transient in the Hall voltage which results after a light pulse has produced nonequilibrium carriers. The type of the excess carriers, electrons or holes, can be determined from the sign of the Hall voltage. An advantage over capacitance-DLTS is that no Schottky barrier is needed, while a disadvantage is that a magnetic field is required. Again, it is too early to tell if this technique will become widely used.

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