# IN-SITU CHARACTERIZATION OF CARRIER MOBILITY IN FIELD EFFECT TRANSISTORS

Andreas G. Andreou

Department of Electrical and Computer Engineering
The Johns Hopkins University
Charles and 34th Streets
Baltimore, MD 21218, USA.

## INTRODUCTION

The Field Effect Transistor (FET) is today the basic element of Very Large Scale Integrated (VLSI) digital systems. FETs are also used in analog circuits for high frequency (microwave) applications. Different types of FETs are the Metal Oxide Semiconductor Field Effect Transistors (MOSFETs), the MEtal Semiconductor Field Effect Transistors (MESFETs) and the MOdulation Doped Field Effect Transistors (MODFETs).

One of the most important physical parameters directly related to the performance of field effect transistors is the carrier mobility. Mobility $\mu$ is defined as the proportionality constant between the applied electric field E, and the average velocity $<v>$, of the carriers

$$<v> = \mu E \tag{1}$$

In simple terms, mobility is a measure of how easy it is for the charge carriers to move in the channel of the device without suffering collisions. In general, it depends on the degree of conduction and it is strongly affected by the chemical and metallurgical aspects of fabrication, in particular the spatial distribution of various impurities and lattice defects, as well as the interaction between them. This is why carrier mobility has a significant effect on the speed, the dynamic range of operation, the frequency response, and the noise characteristics of FETs. It is thus clear, that *in-situ* quantitative evaluation of the mobility is important for improving and optimizing the fabrication procedures as well as for modeling and simulation purposes.

The experimental methods for obtaining the mobility and its dependence on the biasing conditions can be broadly divided in two categories:

- Electrical Measurements
- Galvanomagnetic Measurements

Pure electrical measurements have been used in both MOSFET type devices [1],[2] as well as MESFETs and MODFETs [3],[4],[5],[6]. A procedure for obtaining the mobility involves measurement of the I-V characteristics or the transconductance in a region that the device has linear (ohmic) behaviour. From the measured conductance or transconductance and a knowledge of the number of carriers contributing in the conduction process, mobility can be determined. Unfortunately, the carrier concentration and its spatial dependence (for MESFET devices) is often unknown and thus an additional measurement is required. For large devices this is possible, since a measurement of the variation in the gate capacitance with the applied voltage can give the additional information. This is often referred to as a C-V measurement. For short channel devices, an accurate determination of the capacitance free of parasitics is a formidable task and introduces additional sources of error. Often, carrier concentration profiling is performed on a large capacitive structure which is different than the device itself.

The above problems are avoided if galvanomagnetic measurements are utilized. Techniques involving the Hall effect as well as magnetoresistance/magnetotransconductance measurements can be used to obtain the mobility in the channel **without a priori** knowledge of the carrier concentration. This is the reason that such techniques are preferable over the pure electrical measurements. Furthermore, both the Hall Current (HC) and the Geometrical MagnetoResistance/MagnetoTransconductance (GMR/GMT) techniques are well suited for structures which have large width to length (W/L) ratios, that are common in modern short channel transistors.

## HALL EFFECT MEASUREMENTS

The Hall effect is the manifestation of the Lorentz force on an ensemble of charge carriers constraint to move in a specific direction. The Hall field, is the field induced in the sample such that on the average it balances the effect of the transverse magnetic field, and the charge carriers on the average maintain their original velocity vectors.

The conventional Hall effect characterization technique of semiconductor materials involves the measurement of the Hall voltage $V_H$. These measurements are usually performed in samples that have the long and thin geometry of Fig. 1, or specialized geometries such as the bridge structure, the cloverleaf geometry, or the "Greek cross" shape [1]. The above geometries are necessary to avoid shorting of the Hall field by the contacts.

Using similar structures, it has been possible to extend the measurements from bulk semiconductors to specific devices. Long channel field effect transistors have been fabricated with the additional two contacts for measuring the Hall voltage. Such MOSFET devices, often called "MOS Hall generators" [7], are being used for the investigation of the charge transport including hot electron effects in the inversion layers of silicon MOS devices [8], at room and at cryogenic temperatures.

Hall field mobility studies have also been performed in the surface space charge layers of CdS thin film devices [9] and have been used to investigate the scattering processes in SOS (Silicon On Sapphire) field effect transistors [10], [11]. The cloverleaf configuration with the addition of a Schottky contact can also be used to obtain the spatial profile of the mobility in GaAs epitaxial layers [12] and in modulation doped materials.

However, the need for faster devices with smaller dimensions and the progress in fabrication technology, has produced field effect transistors with a very short active channel length. This shrinking of device dimensions, has introduced a physical constraint on ways that Hall effect measurements can be made. Clearly, the usual long sample configuration

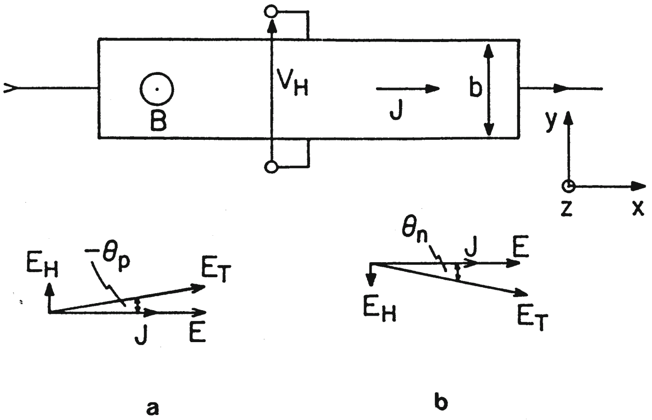

Figure 1. The Hall voltage configuration (a) p-type, (b) n-type.

with two current contacts and the two Hall voltage contacts cannot be used for short channel devices.

## The Hall current method

In the usual Hall effect configuration (Fig. 1), the Lorentz deflection of charge carriers is manifested through the Hall field and the physical quantity measured is the Hall voltage. In the dual configuration (Fig. 2), the geometry of the sample and the position of the contacts prohibits the formation of the Hall field and the charge carriers are deflected by the magnetic field generating the Hall current, another physical quantity that can be measured. Although the two configurations are equivalent, it has been pointed out by Mortensen et. al. [13], that for non-cubic solids the Hall mobilities derived from Hall voltage and Hall current measurements are not identical.

Hall current measurements have been performed in the past on bulk semiconductor materials to study their electronic transport properties. A review of the work in this field can be found in reference [14].

A semiconductor sample configured for Hall current measurements is shown in Fig. 3a. This geometry offers the advantage of requiring only three contacts to the sample and also is the optimum geometry that minimizes the effects of the surface currents [15]. For an n-type homogeneous sample, with uniform contacts on the surfaces, isothermal conditions, negligible magnetoresistance effects $O(\mu B)^2$ and the surface currents, it can be shown [16],[17] that:

$$I_{\mathrm{Hall}} = \frac{a}{b} \mu_H B_z I \tag{2}$$

where b is the thickness of the sample in cm, a is the width of the sample in cm, $\mu_H$ is the Hall mobility in $cm^2/V$ sec, I is the total current injected in the sample ($I = I_1 + I_2$) and $B_z$ is the magnetic induction. The Hall current given by the above formula can be measured by splitting one or both metal contacts into two parts, and measuring the differential current from the two split contacts.

Considering the geometry of Fig. (3a) it can be seen why the Hall current technique can be applied to measure the mobility in field effect transistors. The two contacts A and B will correspond to the drain and source of the FET and the only other geometrical requirement is that either the source or the drain or both, have a split contact.

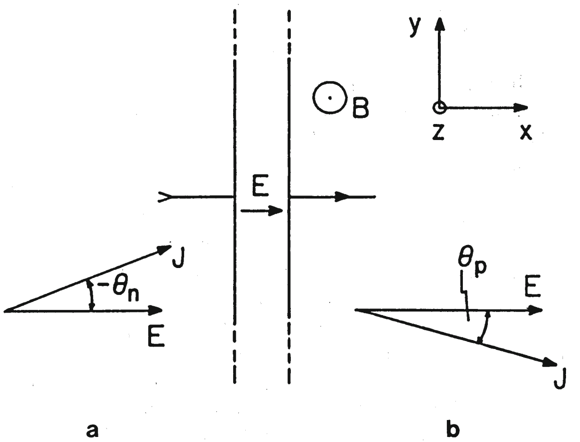

Figure 2. The Hall current configuration (a) n-type, (b) p-type

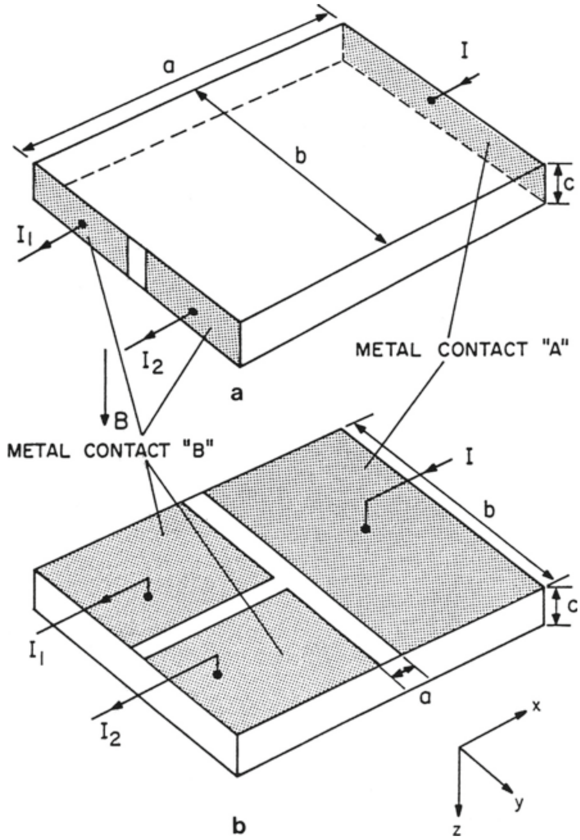

Figure 3. Semiconductor samples configured for Hall current measurements

Devices having this geometry can be readily fabricated and since two voltage contacts are not necessary in the active region of the transistor, this method is compatible with the geometries of modern field effect transistors (short channel).

In principle, the only problem with the short channel devices will be in the actual measurement of the Hall current $I_H$, which depends on the ratio (a/b). For a typical modern GaAs FET transistor this corresponds to (1/250). Thus, the Hall current is scaled down by a factor equal to the above ratio compared to the longer channel structures where the scaling will have an asymptotic value of $\approx 3/4$ [17].

Hall current mobility measurements have been performed on GaAs devices using both a d.c. bridge [15] and an a.c. phase sensitive detection scheme [17]. The latter scheme was used, so that the spatial dependence of the mobility could be obtained in depletion mode GaAs MESFET devices.

The Hall current measurements can also be performed on silicon MOSFETs. The experimental setup for such measurement is shown in Fig. 4. The two operational amplifiers OP1 and OP2 are low noise, low offset devices. These are connected as transresistance amplifiers with the feedback resistance RF1 and RF2 determining their gain. The output of the two op-amps is fed to an instrumentation amplifier IAM whose output voltage is proportional to the differential current from the two source contacts. Note that the two op-amps are connected with their virtual ground input at some potential $V_{SD}$ the bias potential for the device. Both source contacts must be kept at the same potential while measuring the Hall current. This is imposed by the analytical derivation of Eq. (2) where the two metal contacts were assumed to be equipotential surfaces [17].

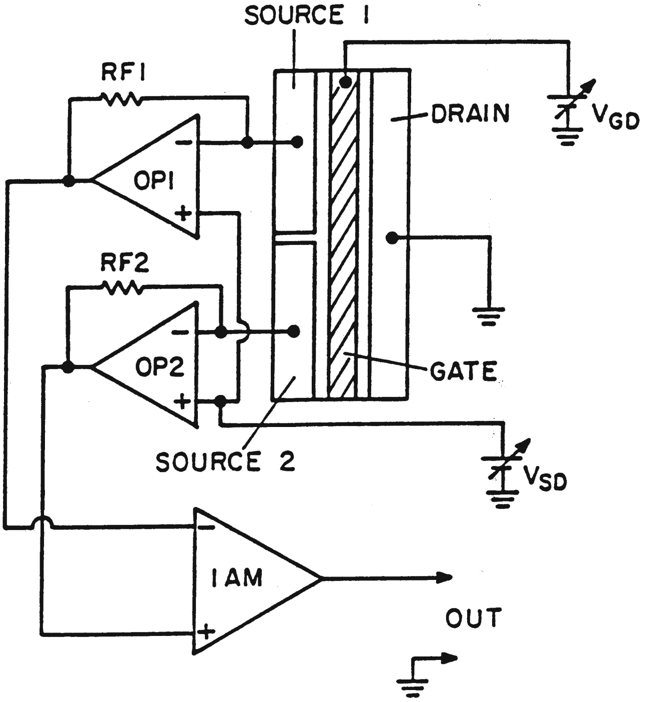

Figure 4. Experimental setup for Hall current measurements on silicon MOSFETs

The experimental results from the above measurements are shown in Fig. 5 where the Hall mobility is plotted as a function of the applied gate-source voltage. The two sets of data on the graph correspond to measurements on two devices, one p-type and the other n-type having similar geometry (W/L=400/130$\mu$m). Note that the mobility values obtained are typical for silicon on sapphire devices with the mobility of the p-type devices about three times smaller than that of the n-type. A small permanent magnet was used to provide the magnetic induction of .25Tesla with a drain-source bias voltage of 200mV.

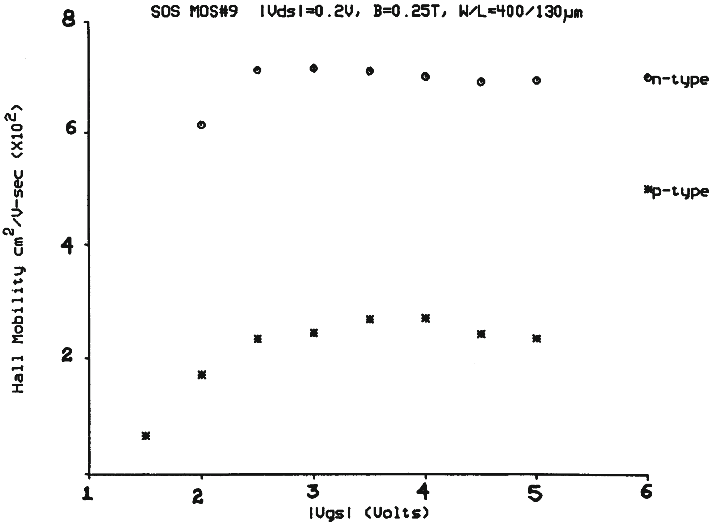

Figure 5. Mobility profiles of SOS MOSFETs obtained using the Hall current technique.

## GEOMETRICAL MAGNETORESISTANCE/MAGNETOTRANSCONDUCTANCE MEASUREMENTS

A very practical method for measuring mobility in the channels of semiconductor FET devices is the Geometrical Magnetoresistance technique (GMR) [18]. The Geometrical Magnetotransconductance (GMT) measurements of Jay and Wallis [19] are an improvement over the GMR method. Both methods have also been used for *in situ* measurements in MODFET's [20]. A comparison between them [21] has shown that the GMT technique gives more reliable information on MODFET's. Furthermore comparison of data obtained from Hall voltage measurements on cloverleaf test structures showed a discrepancy in the position of Hall mobility peaks for the two methods, another indication that *in situ* device measurements are necessary for studying short channel devices. Refinements and improved formulae to interpret the experimental data from GMR and GMT experiments have been developed in [22] and [23]. All the above measurements were performed at low frequencies using phase sensitive detection schemes. Frequencies were usually above 5Khz to avoid the 1/f noise problems encountered in GaAs devices operated at low frequencies [16].

On application of a magnetic field the channel resistance of a MESFET increases because of the GMR effect. For a magnetic field strength B, the resistance R of a slab of semiconducting material changes to a value $R'$ where,

$$R' = R(1+\mu^2 B^2) \qquad (3)$$

and $\mu$ is the mobility of the carriers in the material [16]. This equation assumes that the geometry of the sample and the positioning of the contacts are such that the Hall field in the sample is completely shorted. MESFET's with short gate lengths, compared to channel width satisfy this geometrical constraint. Therefore from (3), the mobility of carriers in the channel of a MESFET can be obtained by measuring the resistance of the channel with and without a magnetic field. It should be pointed out however, that for a given gate voltage, a GMR measurement yields only the average mobility over the active channel and does not yield the mobility at a particular depth in the channel.

Truly differential mobility profiling can be achieved by using the GMT technique. The transconductance $g_m$ of a transistor is a measure of its effectiveness in converting a small voltage variation at the gate to a current variation between the drain and source. As explained in [19], the transconductance of MESFET's in the linear region can be related to carrier mobility in the channel.

A distinct advantage in measuring $g_m$ as compared to channel resistance (for obtaining mobility) is that $g_m$, being an ac parameter, takes into account small modulations at the edge of the depletion layer. Hence, a true mobility profile can now be obtained as a function of depletion layer depth as opposed to only a weighted average provided by GMR measurements. For a MESFET with a channel resistance $R_C$, parasitic source and drain resistances equal to $R_P$, the measured GMT is given by,

$$g_m(B) = \frac{g_m(0)}{1+\mu_C^2 B^2}\left[1+\frac{R_P(1+\mu_P^2 B^2)}{R_C(1+\mu_C^2 B^2)}\right]^{-2} \qquad (4)$$

Here $g_m(B)$ and $g_m(0)$ are respective transconductances with and without a magnetic field. $\mu_p$ is the effective mobility for carriers as they traverse the regions that contribute to the parasitic resistances. Mobility can thus be obtained from transconductance data with and without a magnetic field provided the effects of the parasitic resistances can be taken into account.

As a result of these parasitics, measured $g_m$ is significantly different from the actual $g_m$ at low values of $| V_{GS} |$. However, it can be argued [19] that the ratio of real transconductances with and without a magnetic field follows closely, the ratio of respective measured transconductances. Hence, as far as mobility measurements are concerned, it is sufficient to know measured $g_m$ and (4) can therefore be simplified to yield,

$$g_m = \frac{g_m(0)}{1+\mu_C^2 B^2} \tag{5}$$

The mobility $\mu_C$ can be readily obtained from the above formula. An extension of the low frequency magnetotransconductance measurements are the high frequency measurements (microwave) of Ayyar et. al. [24]. The problems associated with the low frequency measurements were avoided by obtaining the transconductance and its changes with the magnetic field using a microwave network analyzer. The results of both the high frequency and low frequency measurements were virtually identical.

## GEOMETRY CORRECTIONS

The need for a geometry correction arises because our analysis and the derivation of Eq. (2) was done for the idealized geometry Fig. 3a. The difference in the two geometries has to do with the value of the electric field in the sample. For the parallel geometry of Fig. 3a, neglecting any effects from the gap in the split metal contact B, a uniform electric field exists in the sample which is equal to E = V/a where V is the applied potential between contacts A and B; and a is their separation distance †. For the geometry Fig. 3b this is not true. Nevertheless, the field in the samples can be determined using conformal mapping techniques or a numerical method. This problem has been solved in conjunction with the electric field in semiconductor samples used in modulation spectroscopy experiments [25]. The electric field in the middle of the gap of Fig. 3b can be written as

$$E = \varsigma \frac{V}{a} = \frac{V}{\left(\frac{a}{\varsigma}\right)} \tag{6}$$

where $\varsigma$ is a constant that depends on the dimensions of the sample and the separation between contacts A and B. This functional dependence can be given in terms of complicated elliptic functions [26].

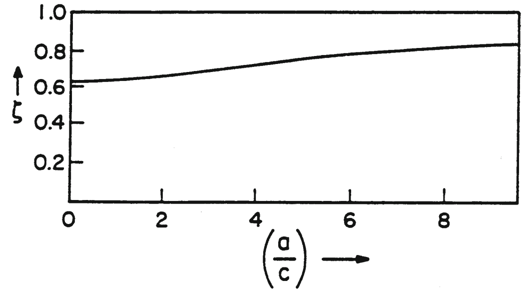

Figure 6. Geometry correction for GaAs MESFET devices

---

† The gap in the split source contact has negligible effect in the measurements when its length is small compared to the width of the sample. This has been verified by numerical simulations.

In our geometries where the metallized plates are large compared to the separation between contacts A and B, the functional dependence is simplified and becomes only a function of the ratio a/c. This is plotted in Fig. 6 for different ratios a/c. From Fig. 6 and Eq. (6) it can be seen that the correction can be applied by replacing the value of the dimension a in Eq. (1) with another $a^*$ where $a^* \equiv a/\varsigma$. For the HFET-5001 devices that we have studied [15],[17], $a = 4\mu m$ and the thickness of the epitaxial active layer $c = 0.18\mu m$ so that $\varsigma = 0.8$.

## CONCLUSIONS

In this paper we have reviewed various techniques for **in-situ** measurement of the carrier mobility in field effect transistors. We have described galvanomagnetic measurements suitable for GaAs MESFETs and MODFETs as well as MOSFET devices. The GMR/GMT techniques are best suited for characterizing devices fabricated on high mobility materials such as GaAs. These measurements are based on the magnetoresistance effect which is $O(\mu B)^2$ and hence they require high values for the mobility/magnetic-induction product††. The Hall current technique has also been described and we have presented experimental results from silicon on sapphire MOSFET devices. The latter method is suitable for devices fabricated on silicon because it is based on the Hall effect which is $O(\mu B)$ and therefore it doesn't require high magnetic fields. Both methods are preferable to plain electrical measurements because they offer a true measure of mobility.

## REFERENCES

1. H.H. Wieder, *Laboratory Notes on Electrical and Galvanomagnetic Measurements* , (Elsevier,New York, 1979)
2. Mong-Song Liang et. al., IEEE Trans. Electron Devices, ED-33, 409 (1986).
3. P.A. Folkes, Appl. Phys. Lett., 48, 431 (1986).
4. R.A. Pucel and C.F. Krumm, Electronics Letters, 12 240 (1976).
5. K. Lehovec, Appl. Phys. Lett., 25 279 (1974).
6. K. Shenai and R. Dutton, IEEE Trans. Electron Devices, ED-35 578 (1988).
7. R.C. Gallagher and W.S. Corak, Solid-State Electronics, 9 571 (1966).
8. K. Hess, Solid-State Electronics, 21 123 (1978).
9. A. Waxman et. al., J. Appl. Physics, 36-1 168 (1965).
10. Jong-Hyun Lee et. al., Solid-State Electronics, 25 947 (1982).
11. A.C. Ipri, Appl. Physics Lett., 20-1 1 (1972).
12. T.L. Tansley, J. Phys. E: Sci. Instr., 8 52 (1975).
13. O.S. Mortensen, R.W. Munn, D.F. Williams, J. Appl. Phys., 42 1192 (1971).
14. V.N. Dobrovol'skii and A.N. Krolevets, Sov. Phys. Semicond., 17-1 1 (1983).
15. A.G. Andreou and C.R. Westgate, Proceedings IEEE (Letters), 73 489 (1985).
16. A.G. Andreou, The Hall Effect and Related Phenomena In Microelectronic Devices, Ph.D. Dissertation, The Johns Hopkins University, (1986).
17. A.G. Andreou and C.R. Westgate, IEEE Trans. Electron Devices, ED-34 1441 (1987).
18. J.R. Sites and H.H. Wieder, IEEE Trans. Electron Dev., ED-27 2277 (1980).
19. P.R. Jay and R.H. Wallis, IEEE Electron Device Lett., EDL-2 265 (1981).
20. D.C. Look, G.B. Noris, W. Kopp, T. Henderson and H. Morkoc, Appl. Phys. Lett., 47 267 (1985).
21. J.P. Harrang, R.J. Higgins, R.K. Goodall, R.H. Wallis, P.R. Jay and P. Delescluse, J. Appl. Phys., 58 4431 (1985).
22. D.C. Look and T.A. Cooper, Solid-State Electronics, 28 521 (1985).
23. K.M. Lau and J.C. Liou, Proceedings of the 44th Annual Device Research Conference, (1986).
24. S. Ayyar, A.G. Andreou, C.R. Westgate, Proceedings of the IEEE Microwave Theory and Techniques Symposium (1988).
25. M. Cardona, *Modulation Spectroscopy*, Solid State Physics, Supplement 11, Academic Press, New York, (1969).
26. Von S.Oberlander und W.E. Wilhelm, Phys. Stat. Sol., 12 569 (1965).

---

††The product $\mu B$ is usually less than unity