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Low electron mobility of field-effect transistor determined by modulated magnetoresistance

R. Tauk,^{a)} J. Łusakowski,^{b)} W. Knap,^{b)} and A. Tiberj
GES CNRS—UMR 5650, Université Montpellier 2, Place E. Bataillon, 34950 Montpellier, France

Z. Bougrioua, M. Azize, and P. Lorenzini
CRHEA—CNRS, rue Bernard Gregory, 06560 Valbonne, France

M. Sakowicz and K. Karpierz
Institute of Experimental Physics, Warsaw University, Hoża 69, 00-681 Warsaw, Poland

C. Fenouillet-Beranger and M. Cassé
CEA LETI, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France

C. Gallon, F. Boeuf, and T. Skotnicki
STMicroelectronics, 850 rue J. Monnet, BP 16, 38921 Crolles, France

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Room temperature magnetotransport experiments were carried out on field-effect transistors in magnetic fields up to 10 T. It is shown that measurements of the transistor magnetoresistance and its first derivative with respect to the gate voltage allow the derivation of the electron mobility in the gated part of the transistor channel, while the access/contact resistances and the transistor gate length need not be known. We demonstrate the potential of this method using GaN and Si field-effect transistors and discuss its importance for mobility measurements in transistors with nanometer gate length. © 2007 American Institute of Physics. [DOI: [10.1063/1.2815610](https://doi.org/10.1063/1.2815610)]

I. INTRODUCTION

Standard methods to determine the mobility in transistor channels are based on static parameter extraction^{1,2} or split capacitance measurements.^{3,4} These methods are difficult to apply to nanometer transistors. In the case of nanometer high electron mobility transistors (HEMTs), the gate covers only a small part of the source-drain distance (see Fig. 1) and the resistance of the contacts (drain and source) and of the access (ungated part of the channel) is much larger than the resistance of the gated region, especially in the transistor “on” state. Therefore, a large correction to the total transistor resistance is necessary in order to effectively analyze the properties of the gated region of the channel. For this reason, advanced models have been developed to determine the series resistance in metal–oxide–semiconductors field-effect transistors (MOSFETs).^{5,6}

Another difficulty in using the standard methods to determine the mobility is related to the evaluation of the gate length. In HEMTs, the length of the part of the channel influenced by the gate is larger than the geometrical length of the gate and the correction is equal to approximately to two times the barrier thickness.⁷ In MOSFETs, one defines different characteristic lengths related to the gate (e.g., mask, metallurgical, electrical⁸) which reflects the fact that the gate length cannot be determined precisely in nanometer devices.

An alternative method to determine the mobility in field effect transistors is a direct current magnetoresistance (dc MR) method. This method is based on measurements of the

transistor resistance in a magnetic field and allows one to determine the electron mobility without knowledge of the geometrical parameters of the transistor (including the gate length), the carrier density, or any other electrical/material parameters of the transistor. This approach is based on the fact that the transistor resistance increases with magnetic field (B) as $\mu_{\text{MR}}^2 B^2$, where μ_{MR} is the magnetoresistance mobility. This effect, called the geometrical magnetoresistance, appears when the length of the channel is much shorter than its width, and is directly related to measurements of the magnetoresistance in the Corbino geometry.^{9–11}

The dc MR method is a well established way of characterizing semiconductor devices. It has been used, for example, to characterize GaAs/AlGaAs-based field-effect transistors with the gate length of the order of 100 μm and the mobility of the order of $5 \times 10^4 \text{ cm}^2/\text{V s}$.¹² In such a case, when the electron mobility is high, the magnetic field required to determine the geometrical magnetoresistance can be much smaller than 1 T, if one assumes that $\mu_{\text{MR}}^2 B^2$ can be measured with the accuracy of 1%. On the other hand, the electron mobility in nanometer Si MOSFETs is of the order of 100 $\text{cm}^2/\text{V s}$ only at room temperature and to observe a geometrical magnetoresistance of 1% one requires magnetic fields of the order of 10 T.¹³ When only standard electromagnets generating a maximum field of the order of 1 T are available, the required accuracy in resistance measurements must be much better than 10^{-4} in order to use the magnetoresistance method to determine the mobility in a typical MOSFET.

The dc MR method was recently applied at high magnetic fields to nanometer bulk¹³ and silicon-on-insulator (SOI)¹⁴ Si MOSFETs and also Si MOSFETs with different

^{a)}Electronic mail: tauk@ges.univ-montp2.fr

^{b)}Also at: Institute of Experimental Physics, University of Warsaw, Hoża 69, 00-681 Warsaw, Poland.

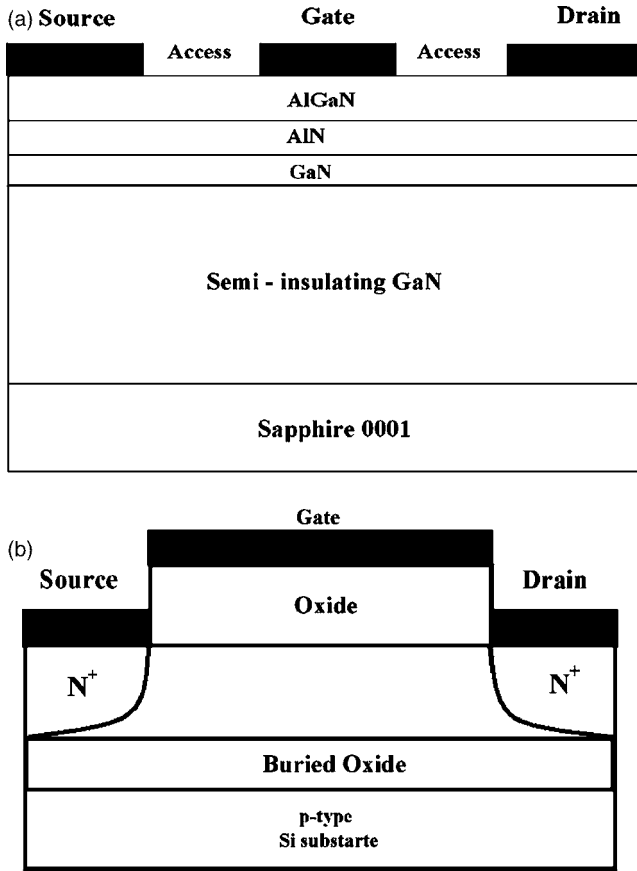


FIG. 1. (a) Scheme of GaN/AlGaIn HEMT transistor showing the source, drain and gate electrodes, and access parts. (b) Scheme of Si MOSFET with the gate extending over the entire source-drain distance (there are no access parts).

architectures.^{15,16} This method was also used to reveal the ballistic motion contribution to the room temperature conductivity in a nanometer Si MOSFET.^{17,18}

Although the dc MR method described in Ref. 13 is free from the problem of determining the gate length, it still requires a correction related to the series resistances,^{10,16} especially in the on state of the transistor.

The influence of the series resistances can be eliminated using the modulated gate voltage magnetoresistance method (ac MR). In this method, one measures the magnetic field dependence of the first derivative of the resistance of the gated part of the channel. Recently, the ac MR method was used to determine the mobility in micrometer GaN/AlGaIn HEMTs.¹⁹ However, in this earlier work we investigated high electron mobility GaN/AlGaIn heterostructures at a temperature of 4.2 K. The low temperature allowed the condition, $\mu B > 1$, to be satisfied, leading to the observation of Shubnikov–de Haas (SdH) oscillations. We used the SdH oscillations to determine precisely the electron concentration in the gated and ungated parts of the channel. The ac MR method described in Ref. 19 cannot be applied directly to study field-effect transistors with a relatively low carrier mobility such as Si MOSFETs since the condition $\mu B > 1$ would require fields of the order of 100 T.

The motivation of the present paper is to check the possibility of application of the ac MR method in the case when

the electron mobility is small and it is not possible to determine the carrier concentration from the SdH oscillations.

As previously mentioned, the ac MR method requires measurements of the first derivative of the transistor resistance with respect to magnetic field (and not the resistance itself, as in the dc MR method). This eliminates the influence of the series and access resistances but necessitates the consideration of the derivative of the mobility with respect to the gate voltage (or the electron concentration). Therefore, another motivation of this work was to verify, how the functional dependence of the mobility on the carrier concentration influences the results of ac MR experiments. In this work we apply the ac MR method to investigate room temperature mobility in GaN/AlGaIn HEMTs and Si MOSFETs.

II. THE AC MR METHOD

A field-effect transistor is a nonuniform structure that is composed, in general, of the source and drain metallic contacts, the access regions, and the gated region. Figure 1 shows a scheme of a GaN/AlGaIn HEMT and a fully depleted SOI (FD SOI) high- k Si MOSFET structure. There are no access regions in MOSFETs, where the gate covers the whole distance between the source and the drain, and slightly overlaps these contacts. The transistor resistance in a magnetic field is equal to

$$R = R_{SD0}(1 + \mu_{SD}^2 B^2) + R_{A0}(1 + \mu_A^2 B^2) + R_{C0}(1 + \mu_C^2 B^2). \quad (1)$$

The terms in Eq. (1) describe, respectively, the magnetoresistance of the source and drain, the access region, and the gated region. Here, R_{SD0} , R_{A0} , and R_{C0} are the associated resistances of the source and drain electrodes, the access region, and the gated region at $B=0$, while μ_{SD} , μ_A , and μ_C are the corresponding magnetoresistance mobilities. The earlier formula is valid for $\mu^2 B^2 \ll 1$, i.e., in the range of weak magnetic fields and when the condition given by $L_D \ll W$ is fulfilled (L_D and W are the device length and width, respectively).^{9–11} $R_{C0} = L/(ne\mu W)$, where L is the length of the gate.

By measuring R as a function of B^2 , one obtains the direct current magnetoresistance mobility

$$\mu_{DC}^2 = (R_{SD0}\mu_{SD}^2 + R_{A0}\mu_A^2 + R_{C0}\mu_C^2)/(R_{SD0} + R_{A0} + R_{C0}). \quad (2)$$

The dc MR mobility, μ_{DC} , is equal to μ_C only if R_{SD0} and R_{A0} are much smaller than R_{C0} .¹⁹ To avoid the problem introduced by nonzero series and access resistances, one applies the ac MR technique to measure the derivative of the transistor resistance as a function of the magnetic field. The measured signal is equal to

$$dR/dU_G = dR_{C0}/dU_G + [d(R_{C0}\mu_C^2)/dU_G]B^2, \quad (3)$$

where U_G is the gate voltage. R_A and R_{DC} do not enter Eq. (3) because they are not affected by the gate potential. Equation (3) shows that the first derivative of R is expected to be a parabolic function of the magnetic field with the coefficients dR_{C0}/dU_G and $[d(R_{C0}\mu_C^2)/dU_G]$. Measurements of the derivative as a function of B^2 allow one to determine the

TABLE I. Parameters of the GaN/AlGaIn HEMTs investigated.

HEMT GaN/AlGaIn	GaN thickness (μm)		AlGaIn		Dislocations (cm^{-2})	L_G (μm)	L_{SD} (μm)
			% Al	Thickness (nm)			
A	S1	4.7	21	23	7.8×10^8	1	5
	S2					21	30
C	S3	7.3	25	25	4.7×10^8	21	30

alternating current mobility (ac MR mobility) μ_{AC}^2 equal to

$$\mu_{AC}^2 = \frac{d(R_{C0}\mu_C^2)/dU_G}{dR_{C0}/dU_G} = \mu_C^2 \left[1 - 2 \left(\frac{1}{\mu_C} \frac{d\mu_C}{dU_G} \right) \left(\frac{1}{\mu_C} \frac{d\mu_C}{dU_G} + \frac{1}{n} \frac{dn}{dU_G} \right) \right], \quad (4)$$

where n is the electron concentration in the gated part of the channel. One can see that μ_{AC} is equal to the channel mobility if the channel mobility is independent of the gate voltage ($\mu_C = \mu_{AC}$ if $d\mu_C/dU_G = 0$).

In previous work,¹⁹ the carrier concentration was determined from SdH oscillations. The approach of the present work is different. We suppose that $n = (\epsilon WL/d)(U_G - U_{TH})$, where ϵ is the dielectric constant, d is the gate-channel distance and U_{TH} is the threshold voltage, determined from the transfer characteristics. Then, $(1/n)(dn/dU_G) = (U_G - U_{TH})^{-1}$ and

$$\mu_{AC}^2 = \frac{d(R_{C0}\mu_C^2)/dU_G}{dR_{C0}/dU_G} = \mu_C^2 \left[1 - 2 \left(\frac{1}{\mu_C} \frac{d\mu_C}{dU_G} \right) \left(\frac{1}{\mu_C} \frac{d\mu_C}{dU_G} + \frac{1}{U_G - U_{TH}} \right) \right]. \quad (5)$$

Equation (5) is the basis of the ac MR method.

It is important to note that Eq. (5) does not contain either ϵ or any of the geometrical parameters (W, L, d) of the transistor. A measurement of μ_{AC} can therefore be a very useful method to determine the mobility in the gated part of the transistor channel.

III. EXPERIMENTAL AND RESULTS

Figure 1 shows schematically the structure of layers and the position of electrodes for both types of transistors studied. Table I gives parameters of GaN/AlGaIn HEMTs used in the present study. GaN/AlGaIn transistors were processed using a metalorganic chemical vapor deposition heterostructure grown on (0001) sapphire. The dislocation density was determined using atomic force microscopy. The transistors were $W=150 \mu\text{m}$ wide and the gate was symmetrically placed between the source and the drain. One transistor and a Hall bar processed on heterostructure C, and two transistors on heterostructure A were studied. The two heterostructures differed in that heterostructure C had an additional 1 nm-thick AlN layer deposited on the GaN/AlGaIn interface.²⁰ In the case of the FD SOI high- k Si MOSFETs, the gate length and width were $L=1 \mu\text{m}$ and $W=10 \mu\text{m}$. The gate stack was composed of an HfSiON dielectric (3 nm) covered by 10

nm of TiN, the thickness of the buried oxide and Si channel was 140 and 8 nm, respectively, and the channel doping was $1 \times 10^{15} \text{ cm}^{-3}$.

The transistors were mounted in a sample holder which was placed in the center of a 10 T superconducting coil immersed in liquid helium at 4.2 K. Due to the thermal isolation between the sample holder space and the helium bath, the temperature of the transistors could be adjusted and stabilized between 4 and 300 K. The measurements on the GaN/AlGaIn and Si transistors were performed at 4.2 and 300 K, respectively. The ac MR measurements were carried out by sweeping the magnetic field up to 1 T for GaN/AlGaIn HEMTs and up to 10 T for the Si MOSFETs. A constant current was applied to the transistors (such that they operated in the linear part of the output characteristics) and the gate potential was composed of a dc bias on which a small (20 mV peak to peak) sinusoidal 1 kHz modulation was superimposed.

The ac signal of the source-drain voltage is equal to the derivative of the channel resistance and in each case was found to be proportional to B^2 . The ac component was registered by a lock-in technique and the phase of the signal was kept constant for all gate voltages. The phase of the signal must be carefully considered in this experiment because the sign of the derivatives in Eq. (5) may change as a function of U_G . Simultaneously, a dc source-drain voltage was recorded and used to determine the dc MR mobility.

We first describe results obtained on GaN/AlGaIn transistors. Figure 2(a) shows the ac signal for transistor S2 (the heterostructure A) as a function of the B^2 for several gate voltages. We would like to stress that the measured $(dR/dU_G)(B)$ dependences were always parabolic in B (linear in B^2) to a very good approximation. One should also note that the signal (dR_{C0}/dU_G) at $B=0$ can change sign from positive to negative at a certain gate voltage. A similar behavior was observed for all the transistors studied. The dc magnetoresistance, i.e., $R(B)$, was also always linear [see Fig. 2(b)] in B^2 , and this made it possible to determine μ_{DC} , according to Eq. (2). Data shown in Fig. 2 together with Eq. (5) allowed us to determine μ_C as a function of U_G (see later).

We used transistor S3 (based on heterostructure C) to compare the mobility determined from ac and dc magnetoresistance methods. We also measured the Hall mobility (μ_H) on a test gated Hall bar structure adjacent to the transistor S3. Figure 3 shows μ_{AC} , μ_{DC} , and μ_H as a function of the gate voltage. We observed that the Hall mobility and the ac MR mobility are in a perfect agreement proving the validity of the ac MR method. We also note that $\mu_{DC} = \mu_H = \mu_C$ for a

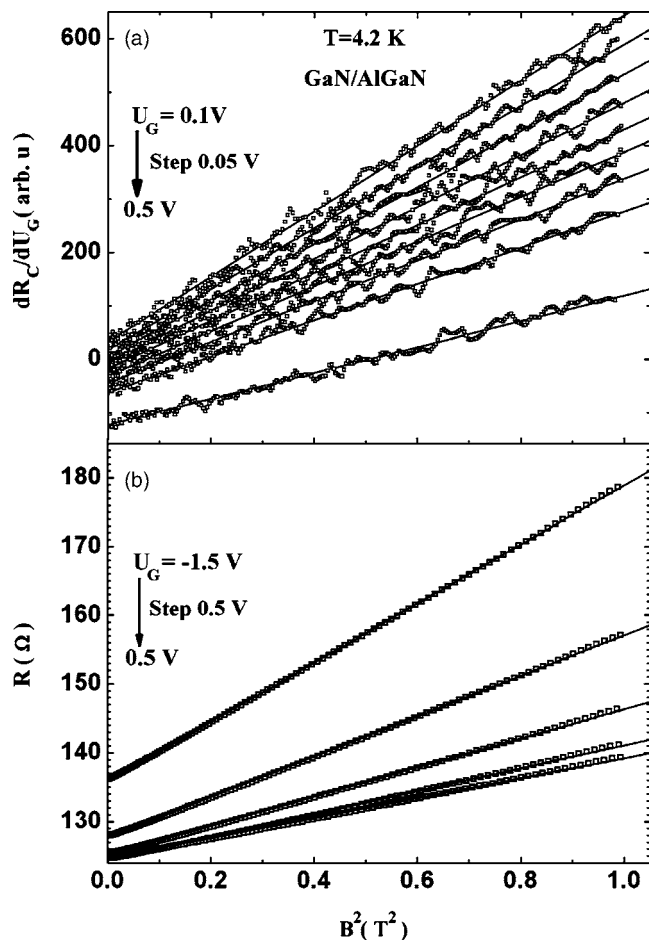


FIG. 2. (a) ac MR signal dR_C/dU_G as a function of B^2 for the transistor S2 for different values of U_G (0.1–0.5 V with 0.05 mV step, top to bottom). (b) dc MR signal for U_G (–1.5 to 0.5 V with 0.5 V step, top to bottom). Solid lines are linear fits.

closed channel transistor. This follows from the fact that when $U_G \sim U_{TH}$ the access and contact resistances are much smaller than the channel resistance and do not affect the results of the dc MR method [see Eq. (2)].

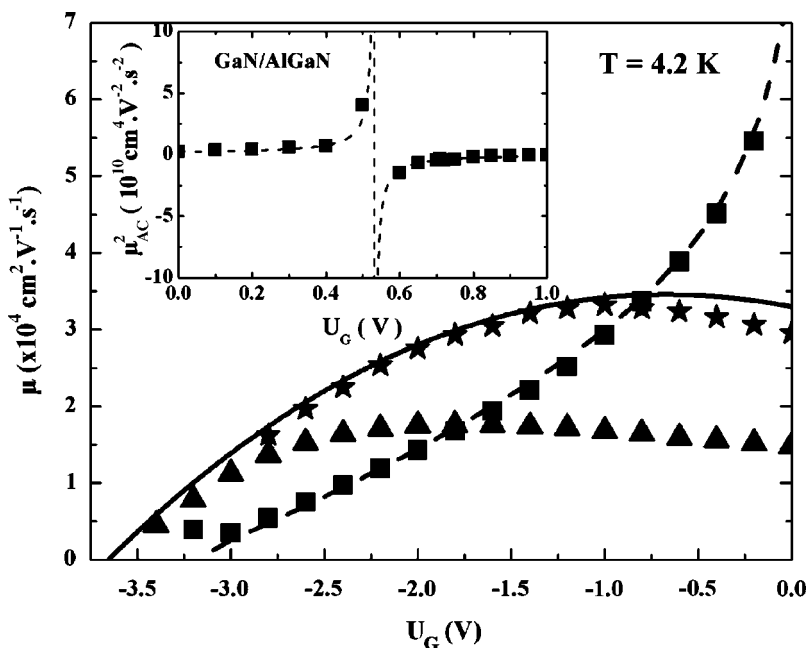


FIG. 3. Hall mobility (stars), dc MR mobility (triangles), and ac MR mobility (squares) as a function of the gate polarization for the Hall bar and S3 transistor on GaN/AlGaN heterostructure C, respectively. Solid line: the carrier mobility derived from the ac MR method, dashed line: fitting of Eq. (5) to experimental data of μ_{AC} . The inset shows the experimental singularity (squares) observed in the S3 transistor when the carrier density (the gate voltage) is increased; the dashed line is the fit using Eq. (5).

Solving Eq. (5) directly to find $\mu_C(U_G)$ is a difficult task. The Hall bar measurements show, however, that the mobility versus gate voltage dependence has a bell-like shape which can be approximated to a high accuracy with a third order polynomial. We used such a polynomial approximation of μ_C in the procedure of fitting $\mu_{AC}^2(U_G)$ in Eq. (5) to the experimental data. An example of a $\mu_{AC}^2(U_G)$ fit is shown as a dashed line in Fig. 3. The $\mu_C(U_G)$ function that gave the best fit of the μ_{AC} data is plotted as a solid line in Fig. 3. Its shape is close to the $\mu_H(U_G)$ dependence measured in the Hall bar, which confirms the consistency of the applied procedure. Some discrepancy at higher gate voltages could result from a slight nonuniformity of the wafer (the transistor and the Hall bar were separated by a distance of about 1 mm).

It should be stressed that μ_{AC} differs essentially from μ_C , especially at higher gate voltages at which a singularity-like behavior was observed. This singularity is related to the change of sign of the derivative of the resistance, visible in Fig. 2 and can be described with Eq. (5) (see the inset to Fig. 3). This clearly shows that, in general, μ_{AC}^2 does not have the physical meaning of the square of the mobility. This point will be discussed later in more detail.

Figure 4 shows the results for two GaN transistors, S1 and S2. For both transistors we also observe the divergence of μ_{AC}^2 for a sufficiently high gate voltage, at about 0.35 V. To find the mobility in the channel we fit the experimental results of μ_{AC}^2 using Eq. (5). Since fitting of the data in the singularity region in μ_{AC}^2 can be sometimes numerically unstable, we fit both μ_{AC}^2 and μ_{AC}^{-2} and we present results of fitting in Figs. 4(a) and 4(b) while the resulting mobility is plotted in Fig. 4(c). One can observe that this analysis, carried out for both transistors, gave very close values of the channel mobility.

Figure 5 shows ac MR and dc MR plots for Si FD SOI MOSFETs measured at room temperature. Both types of plots are linear in B^2 but variations of the signal with B are much weaker than for GaN/AlGaN HEMTs. This is a result of a much smaller mobility in Si transistors.

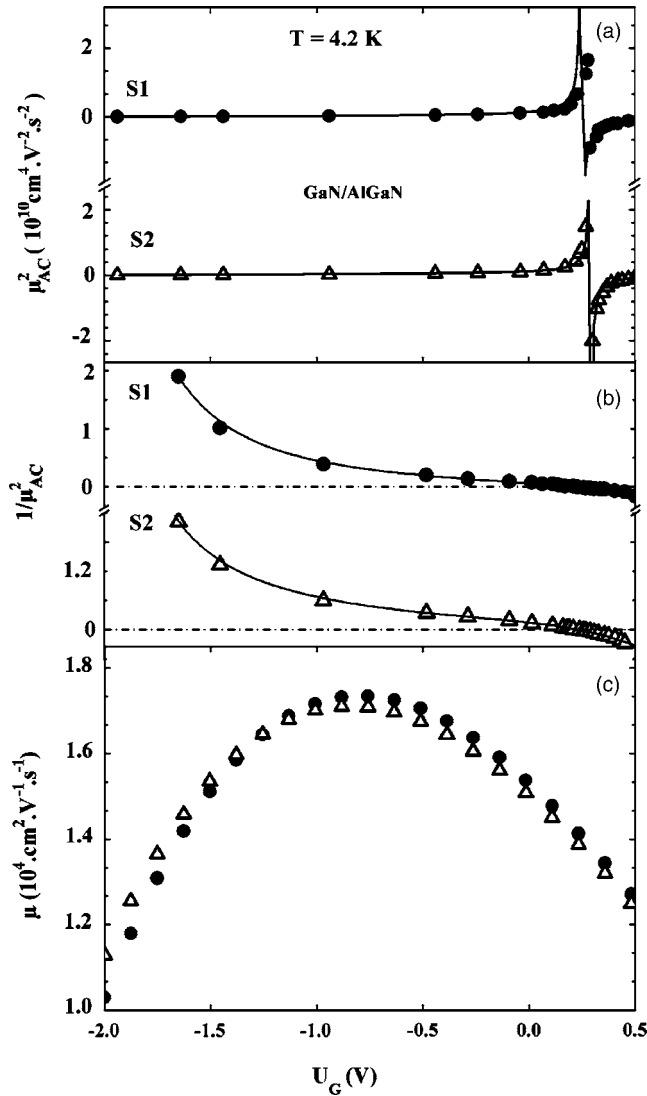


FIG. 4. (a) μ_{AC}^2 as a function of gate voltage at 4.2 K for transistors S1 (circles) and S2 (triangles). (b) $(\mu_{AC}^2)^{-1}$ for S1 and S2 (in $10^{-10} \text{ V}^2 \text{ s}^2/\text{cm}^4$), solid lines are results of fitting. (c) Electron mobility determined by fitting Eq. (5) to data in (a). S1: circles, S2: triangles.

Figure 6 shows experimental data of μ_{AC} (solid triangles), μ_{DC} (solid circles), and the channel mobility μ_C (solid line) resulting from fitting. The quality of the fit can be estimated by comparison of the dashed line and μ_{AC} experimental points. These results are compared with the mobility, μ_{CV} , obtained by split capacitance-voltage (C - V) measurements (open points) for a similar device. The data are presented as a function of the effective electric field $E_{\text{eff}} = e/\epsilon_{\text{Si}}(n/2 + N_a t_{\text{Si}})$, where e is the electron charge, ϵ_{Si} is the dielectric constant of silicon, N_a -channel doping level, and t_{Si} is the channel thickness. The data show a relatively good agreement of results obtained by these two methods.

Figure 6 shows also that the channel mobility, μ_C , extracted from the ac MR measurement is comparable with dc and ac mobility only at small carrier concentrations (weak inversion) because in this region the contact resistance is smaller than the resistance of the channel. The difference between μ_C and μ_{DC} at high gate voltage indicates the influence of the access resistance under open channel conditions.

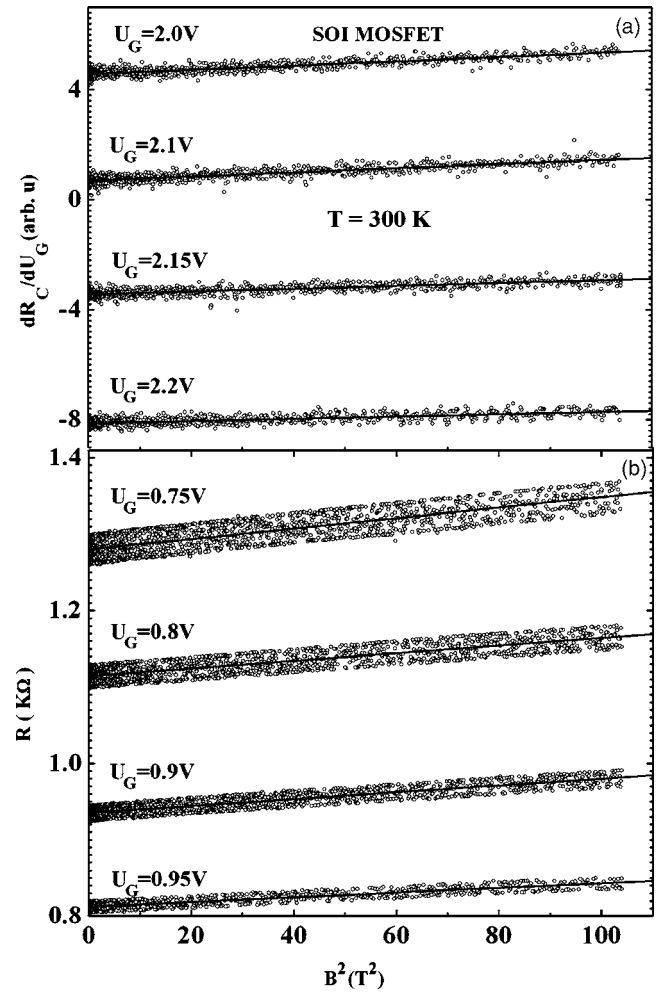


FIG. 5. FD SOI MOSFET with a gate length of $1 \mu\text{m}$; data for $T = 300 \text{ K}$. (a) ac MR signal dR_C/dU_G as a function of B^2 for different gate polarizations U_G . (b) dc MR signal. Solid lines are results of the linear fit.

The inset to Fig. 6 shows that for Si devices one can also observe a singularity in μ_{AC}^2 (solid triangles) which is well reproduced by fitting Eq. (5) to the data (dashed line).

IV. DISCUSSION

The ac MR method eliminates the influence of the series resistances but with the drawback that one has to take into account the derivative of the mobility with respect to gate voltage or carrier density. Therefore, one important motive of this work was to verify how the functional dependence of mobility versus carrier density influences results of ac MR experiments.

Typically, in two-dimensional systems, this dependence shows a bell-like shape. Its physical origin is the interplay between screening and surface/interface related scattering mechanisms.²⁰ At low gate voltages, the mobility increases because screening becomes more efficient with an increase of the carrier concentration. At high gate voltages, carriers are localized close to the channel/barrier interface and the mobility decreases because of an enhancement of the interface- or barrier-related scattering. This bell-like shape of $\mu(U_G)$ may lead, in general, to a divergence of μ_{AC}^2 . The physical origin of such a singularity can be found by a closer

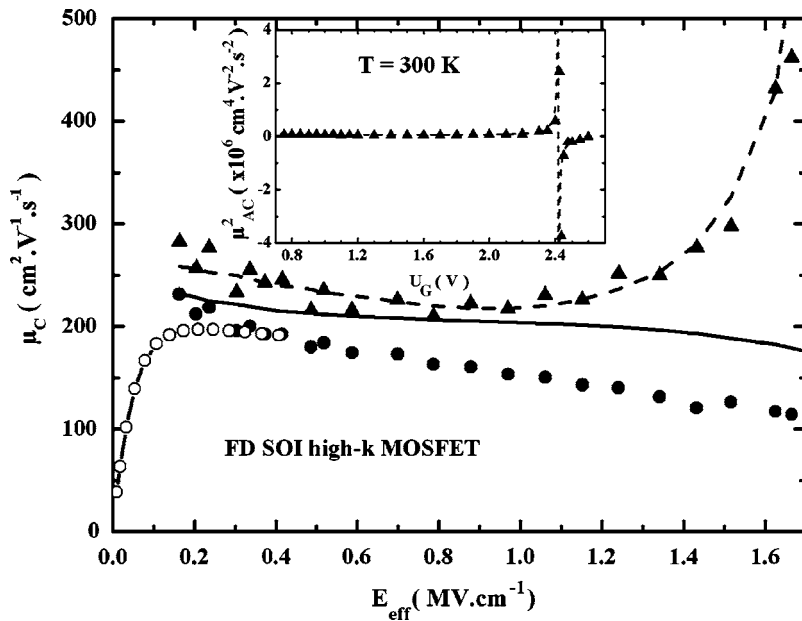


FIG. 6. μ_{AC} (solid triangles), μ_{DC} (solid circles), and μ_{CV} (open circles) as a function of effective field and the solid line is the electron mobility determined by fitting Eq. (5) to the data of μ_{AC}^2 as a function of U_G (dashed line). The inset shows experimental data of μ_{AC}^2 (solid triangles) and fit of Eq. (5) (dashed line) as a function of U_G .

inspection of Eq. (4). One can see that a singularity appears when the first derivative of the channel resistance tends to zero and changes sign. This happens when the mobility decreases with the gate voltage and its relative change μ'_C/μ_C (which is then negative) is larger than the relative increase of the carrier concentration n'/n (which is positive, the prime denotes the derivative d/dU_G). We observed such a coincidence for both GaN/AlGaN HEMTs and Si MOSFETs. This clearly shows that the ac MR mobility, μ_{AC}^2 , defined by Eqs. (4) and (5) is an experimentally measurable quantity useful in the characterization of field effect transistors, but must not be interpreted directly as the square of the mobility.

The ac MR mobility μ_{AC} differs from μ_C in the whole investigated range of U_G except for one particular value of U_G : μ_{AC} is equal to μ_C just at the maximum of the $\mu_C(U_G)$ curve. At such a gate voltage, the derivative of μ_C with respect to U_G is equal to zero and Eq. (5) gives $\mu_{AC} = \mu_C$. This case is very well illustrated in Figs. 3 and 6.

We stress that the procedure to determine the ac MR mobility is not only independent of the access resistance but also of the geometrical dimensions of the transistor (provided $L \ll W$). Therefore, it can be directly applied to study mobility in nanometer gate length devices.

An apparent advantage of the ac MR method is that the measured signal corresponds to the part of the channel that is modulated by the gate. One should note, however, that in the case of MOSFETs there is a small overlap of the gate and heavily doped source and drain regions. Thus, the signal registered in the ac MR method corresponds both to the channel and the overlap region. Therefore, the ac MR mobility is an average mobility corresponding to these two regions. For a HEMT architecture, the gate influences the channel over a length that is greater than the geometrical length of the gate. This is due to the electric field “leaking out” on both sides of the gate. These border effects are negligible for micrometer transistors, but become more and more important when the gate length shrinks to nanometers.

The examples cited earlier show that the ac MR method

allows one to eliminate the influence of the majority of the source/drain and access resistance on the mobility, giving a mobility value that is averaged over the total area modulated by the gate voltage. This is a possible limitation of the precision of the method in the case of nanometer transistors. However, one may argue that for a comparison of different devices/technologies one should not consider a mobility of carriers at some small artificially defined part of the channel (geometrical length of the gate) but rather a “mobility averaged over the total volume modulated by the gate voltage,” therefore validating this approach.

V. CONCLUSIONS

In this work, we have presented the gate modulated magnetoresistance method to determine the electron mobility in GaN/AlGaIn and FDSOI MOSFETs transistors. The ac MR method was applied in conditions usually encountered in characterization of semiconductor devices. The most important advantage of this method is that it automatically allows one to neglect the part of the transistor that is not influenced by the gate voltage. This means that the procedure to determine the mobility does not require any knowledge of the access or contact resistances, nor of the gate length of the transistor. Therefore, this method can be extremely useful for studying mobility in nanometer gate length devices.

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