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Application of the Shubnikov–de Haas Oscillations in the Characterization of Si MOSFET's and GaAs MODFET's

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Abstract—The Shubnikov–de Haas magnetoconductance oscillations were used to measure directly the gate-to-channel capacitance of Si MOSFET's and GaAs MODFET's, to detect the onset of parallel conduction in GaAs MODFET's, and to provide an approximate measure of channel length in sub-100-nm channel of Si MOSFET's. The measurements do not require knowledge of any device parameters, are immune to any gate parasitic capacitance, and are independent of source and drain series resistances. One needs to know only the magnetic field, the oscillation period (for gate-to-channel capacitance measurement), the gate voltage (for detection of the onset of parallel conduction), and the number of oscillation peaks (for the channel length characterization). Experimental results have shown that the characterization methods are accurate, and can be applied to FET's with sub-100-nm channel length.

I. Introduction

CHARACTERIZATION is an important and integral part of the study of semiconductor devices. A new characterization method often provides new information and insight on the nature of device operation or structure. The so-called Shubnikov–de Haas (SdH) oscillations of magnetoconductance have been used extensively to study various aspects of Si inversion layers [1]–[3] (for examples, see [2]). This paper describes the use of the SdH oscillations to measure directly the gate-to-channel capacitance of Si MOSFET's (including ones with sub-100-nm channels) and of GaAs MODFET's, to detect the onset of parallel conduction in GaAs MODFET's, and to provide an independent approximate measure of channel length in Si MOSFET's with sub-100-nm channel lengths.

As explained in the next section, the SdH oscillations refer to oscillations of the drain current or of the transconductance of an FET in a magnetic field, as the magnetic field or the gate voltage is swept.

The gate-to-channel capacitance per unit area of an FET C is one of the most important parameters in FET theory because it links the gate voltage to the channel charge. However, C is usually determined indirectly from a large-area capacitor fabricated on the same substrate. Although this method is in general rather accurate (especially for Si MOSFET's), the direct measurement of C in a particular device is desirable in the many situations. The methods of directly measuring C published in the literature require the channel area to be relatively large and the parasitic capacitance to be small [4]–[7]. Therefore, these methods cannot be used to measure the C of FET's with very short or narrow channels. Using the SdH oscillations, the C of an FET (even when the channel is extremely short or narrow or both) can be determined accurately without requiring knowledge of the parasitic capacitance, the channel area, or other device parameters.

The determination of the onset of parallel conduction in the heavily doped layer of a MODFET is a key issue in both device and circuit design. In the past, C–V measurements have been used to determine the onset of the parallel conduction [8]. This method suffers from the effects of parasitic gate capacitance and parasitic series resistance, and becomes increasingly inaccurate as the gate length or gate width is made smaller. The SdH method is immune to parasitic capacitance and parasitic resistance, and can accurately detect the onset of parallel conduction.

In the study of short-channel FET's, the determination of channel length is essential. When the channel length is of the order of 100 nm, the definition of the channel length itself becomes rather ambiguous. In fact, the channel length of a short-channel FET is usually defined by fitting a model to its electrical behavior. A more direct characterization method would be desirable for devices with very short channel lengths. The SdH method provides a complementary way to evaluate the channel length of short-channel FET's.

In the following sections, we describe the principle of the Shubnikov–de Haas oscillations, and then discuss separately the measurement of gate-to-channel capacitance of Si MOSFET's and GaAs MODFET's, the detection of the onset of parallel conduction in GaAs MODFET's, and the measurement of the flat portion of surface potential in the sub-100-nm channel of a Si MOSFET.

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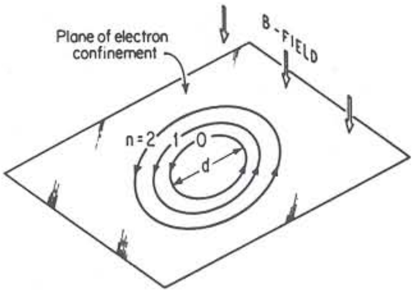

Fig. 1. Illustration of the Laudau quantization.

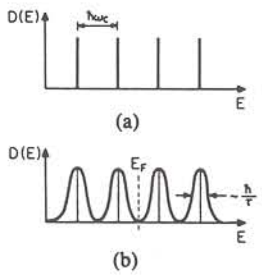

Fig. 2. Illustration of the density of states in the case of (a) no scattering, and (b) with scattering.

II. Shubnikov–De Haas Oscillations

When a magnetic field B is applied normal to the electron conduction plane of an n-channel MOSFET or a MODFET, the electrons in the channel travel in cyclotron orbits, as illustrated in Fig. 1. Because of the requirement of quantum coherence, the allowed cyclotron orbits are those whose circumference is equal to an integral multiple of the electron wavelength. This means that both the energy and the cyclotron orbit diameter are quantized. The quantization is called "Landau quantization." It can be shown [9] that the energies of Landau levels are the same as those of a linear harmonic oscillator

$$E_n = (n + \tfrac{1}{2})\hbar\omega \tag{1}$$

where $n = 0, 1, 2, \cdots$, are cyclotron orbit numbers, $\hbar$ is Planck's constant divided by 2π, $\omega = qB/m^*$, q is the absolute value of the electron charge, and m^* is the effective mass of the electron.

The diameter of the nth cyclotron orbit is given by [10]

$$d_n = d_0\sqrt{2n + 1} \tag{2}$$

where $d_0 = 2\sqrt{\hbar/qB}$ ($d_0 = 51.3/\sqrt{B}$ nm, where B is in tesla) is the diameter of the ground cyclotron orbit ($n = 0$). Since d_0 contains only fundamental constants and B, the orbit diameter does not depend on the material that an FET is made of.

In Landau quantization, the density of states of electrons confined to a two-dimensional plane is no longer constant with energy (as it is in zero magnetic field); instead it is a series of uniformly spaced δ functions in the case of no scattering, or peaks in the case of broadening due to scattering, as depicted in Fig. 2. Because of the periodic character of the density of states, the drain current (and hence the channel conductance and transconductance) of a device can be made to oscillate. This is because the conductivity depends on the number of available states nearby in energy that electrons can scatter into. The conductance peaks whenever the Fermi level and a Landau level are lined up because the density of states has a maximum at each Landau level. Correspondingly, the conductance dips when the Fermi level is between two adjacent Landau levels. When the magnetic field is fixed, so that the Landau level spacing is constant, the drain current can be made to oscillate by varying the gate voltage to move the Fermi level past the discrete Landau levels.

The drain current can also be made to oscillate by varying the magnetic field, while keeping the gate voltage constant. In this case, the Fermi level is unchanged, but the Landau level spacing varies with the magnetic field, and thus the Landau levels sweep across the Fermi level. These two kinds of oscillations are referred to as Shubnikov–de Haas oscillations with gate voltage (SdH-G) and with magnetic field (SdH-M), respectively.

Observation of the SdH oscillations requires that the thermal energy broadening kT and the scattering-induced energy broadening $\hbar/\tau$ be smaller than the Landau level spacing $\hbar\omega$, where k is Boltzmann's constant, T is the temperature, and τ is the momentum relaxation time. This implies that the SdH measurement has to be carried out at low temperatures and that a device has to have a reasonable mobility. The specific values of temperature and mobility that are necessary to observe the SdH oscillation can be estimated from $\hbar\omega > kT$ and $\hbar\omega > \hbar/\tau$, respectively. These expressions give the following two observability criteria for SdH oscillations: $T < 1.3B/(m^*/m_0)$ K and $\mu > 10^4/B\ \text{cm}^2/\text{V}\cdot\text{s}$, where B is in teslas and m_0 is the free electron mass.

III. Direct Measurement of Gate-to-Channel Capacitance (MOSFET and MODFET)

Both SdH-G and SdH-M can be used to measure directly the gate-to-channel capacitance per unit area of a MOSFET or MODFET. In the SdH-G measurement (qV_{DS} should be less than the Landau level spacing to avoid electron transition between Landau levels), the maximum number of electrons per unit area that each Landau level can accommodate ΔN is fixed and given by [11]

$$\Delta N = \frac{g_v qB}{\pi\hbar} \tag{3}$$

where g_v is the valley degeneracy of a semiconductor, which is 2 for (100) Si and 1 for GaAs.[1] When the gate voltage V_{GS} is well above the threshold voltage V_T of the device, the number of electrons per unit area in the channel is related to the gate-to-channel capacitance C by

$$N = \frac{C}{q}(V_{GS} - V_T). \tag{4}$$

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[1] The spin degeneracy equal to two is included in (3), and the interaction of spin and magnetic field (i.e., the spin splitting) is assumed to be negligible compared to Landau level spacing.

Thus

$$\Delta N = \frac{C}{q} \Delta V_{GS} \tag{5}$$

where ΔV_{GS} is the increment of gate voltage necessary to create ΔN, and equals the spacing between adjacent oscillation peaks. (Note that at low temperatures electrons fill up to the Fermi level.) Equating (3) and (5), we have

$$C = \frac{g_v q^2}{\pi \hbar} \left(\frac{B}{\Delta V_{GS}} \right) \tag{6}$$

or

$$C = 7.72 \times 10^{-9} \, g_v \left(\frac{B}{\Delta V_{GS}} \right) \ \text{F/cm}^2 \tag{6a}$$

where B is in tesla, and ΔV_{GS} is in volts. Experimentally, both B and ΔV_{GS} can be measured with good precision, and therefore the gate-to-channel capacitance C of a device can be extracted directly.

In the SdH-*M* measurement, the Fermi level E_F is fixed and so is the electron density in the channel. Then the $1/B$ period of the conductance oscillation is constant and, from (1), is given by

$$\Delta \left(\frac{1}{B} \right) \equiv \left(\frac{1}{B_n} \right) - \left(\frac{1}{B_{n+1}} \right) = \frac{q\hbar}{mE_F} = \frac{g_v q}{\pi \hbar N}. \tag{7}$$

Rewriting (7), we have

$$N = \frac{g_v q}{\pi \hbar \Delta \left(\dfrac{1}{B} \right)} \tag{8}$$

or

$$N = 4.83 \times 10^{10} \frac{g_v}{\Delta \left(\dfrac{1}{B} \right)} \ \text{cm}^{-2} \tag{8a}$$

which means that the electron density can be determined from the period $\Delta(1/B)$. By measuring V_{GS} and $\Delta(1/B)$, we can make a plot of N versus V_{GS}. If the C is independent of gate voltage, the plot is a straight line and the slope is the gate-to-channel capacitance.

The gate-to-channel capacitance C consists of two parts: 1) the capacitance due to the thickness Z_i of the oxide layer in the case of a MOSFET or of the AlGaAs layer in the case of MODFET, and 2) the capacitance due to the average distance Z_{av} between the channel electrons and the semiconductor interface. It is important to note that Z_{av} is a function of gate bias, but for $V_{GS} >> V_T$ it does not vary appreciably. The capacitance is related to the above two distances by

$$\frac{1}{C} = \frac{Z_i}{\epsilon_i} + \frac{Z_{av}}{\epsilon_{sc}} \tag{9}$$

where ϵ_{sc} is the dielectric constant of Si or GaAs, and ϵ_i is the dielectric constant of SiO_2 or AlGaAs. In a MOSFET with an oxide thickness of a few tens of nanometers, the second term in (9) is insignificant because Z_{av} is about 1–5 nm and $\epsilon_{sc} \simeq 3\epsilon_i$. But in a MODFET with an AlGaAs layer thickness of a few tens of nanometers, the second term in (9) may be significant because Z_{av} is about 4–15 nm [12], and GaAs has the same dielectric constant as that of AlGaAs.

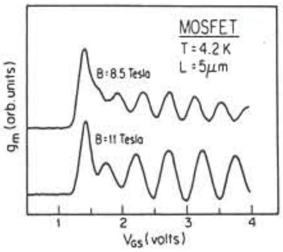

Fig. 3. Transconductance g_m versus gate velocity V_{GS} for a 5-μm-channel MOSFET at different magnetic fields, and V_{DS} = 1 mV.

We have used the SdH-*G* to measure the gate-to-channel capacitance of Si MOSFET's with channel lengths from 80 nm to 5 μm (all fabricated on the same wafer), and nominal oxide thickness of 11 nm, and the gate-to-channel capacitance of GaAs MODFET's with 5-μm-gate length. The MOSFET's were fabricated on (100) Si using a combination of X-ray and optical lithographies, and showed well-behaved *I–V* characteristics at room temperature [13]–[15]. The MODFET's were fabricated using molecular-beam epitaxy. The measurements were carried out at low temperatures (4.2 and 1.2 K) in a Bitter magnet. In order to enhance the oscillation, the transconductance of devices was directly measured using a lock-in amplifier. The source–drain voltage was kept less than the Landau level spacing, i.e., a few millivolts. The applied magnetic field could be determined with an accuracy better than 0.4 T, and the gate voltage could be measured with 20-mV accuracy. This gave an error in the measurements of C smaller than 5 percent.

The 5-μm-channel MOSFET had a low-field electrical mobility of 330 $\text{cm}^2/\text{V} \cdot \text{s}$ at 300 K and 2200 $\text{cm}^2/\text{V} \cdot \text{s}$ at 4.2 K. Its transconductance g_m versus V_{GS} curves at B = 8.5 T and 11 T are given in Fig. 3. As expected, g_m oscillates periodically with gate voltage. The gate voltage was limited to 4 V to avoid oxide breakdown. The spacing between the oscillation peaks is constant. From the spacing of the peaks, the gate-to-channel capacitance calculated from (6) is 3.23×10^{-7} F/cm² at B = 8.5 T, and 3.30×10^{-7} F/cm² at B = 11 T. The relative difference between C's measured at different magnetic fields is 2 percent, which is smaller than the inaccuracy of the measurement. This means that the determination of C is independent of B, as it should be. The capacitance per unit area measured conventionally using a large area gate-oxide capacitor fabricated on the same chip, was 3.20×10^{-7} F/cm², which is also within the 5-percent measurement error.

The SdH-*G* oscillations of a 90-nm-channel MOSFET at two different magnetic fields are shown in Fig. 4. The oscillations differ from those of the 5-μm-channel MOSFET's in that the amplitude of the peaks decays rapidly

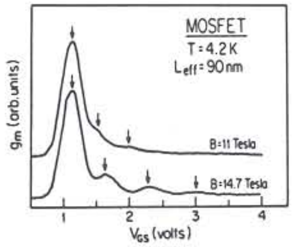

Fig. 4. Transconductance g_m versus gate voltage V_{GS} for a 90-nm-channel MOSFET at different magnetic fields and $V_{DS} = 1$ mV. Arrows indicate the SdH oscillation peaks. (Curves are displaced vertically for clarity.)

with gate voltage. This is caused by the channel length effect, which will be discussed in Section V. However, the oscillation period is constant, and from this the C values calculated from (6) are 3.38×10^{-7} F/cm^2 at $B = 14.7$ T, and 3.35×10^{-7} F/cm^2 at $B = 18.3$ T. These values agree, within the 5-percent measurement error, with the value for the 5-μm-channel MOSFET and the large capacitor.

It should be pointed out that, because of the non-self-aligned structure of our MOSFET's, the gate parasitic capacitance of the sub-100-nm channel MOSFET's is much larger than the gate-to-channel capacitance. However, as expected, the SdH measurement was totally immune to the parasitic capacitance. The physics behind this is that the electrons in the n$^+$ regions are moving in a three-dimensional space (as opposed to a 2-D inversion layer) and have much lower mobility due to high doping; therefore, they do not contribute to the SdH. The observed SdH oscillations result entirely from Landau quantization of two-dimensional electrons in the channel.

The SdH-G oscillations of a 5-μm-gate-length GaAs MODFET at differnt magnetic fields are shown in Fig. 5. When the gate voltage is below -0.1 V, the oscillations of the transconductance of the device are similar to a long-channel Si MOSFET. When the gate voltage is greater than -0.1 V, however, the oscillations become weak. This is caused by "parallel conduction" in the heavily doped AlGaAs layer as discussed in the next section. The gate-to-channel capacitance extracted by the SdH-G is 1.96×10^{-7} F/cm^2 at $B = 2.5$ T, and 1.90×10^{-7} F/cm^2 at $B = 3$ T. As expected, the capacitance is independent of the magnetic field within the experimental error. From the above capacitance values and (9), the thickness of the AlGaAs layer plus the average distance of electrons from the interface ($Z_i + Z_{av}$) is calculated to be 55 nm. Compared with the measurement of the AlGaAs layer thickness by the growth timing method, it suggests that the average distance of electrons from the interface is about 10 nm, which seems a few nanometers longer than expected. This discrepancy may be explained by the fact that the growth rate used in the timing method was calibrated from the growth of thick films (~ 4 μm). However, from SEM micrographs we observed that the growth rate is higher at the start of the growth and hence the timing method underestimates the thickness of thin films.

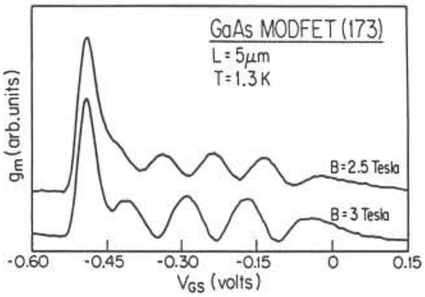

Fig. 5. The SdH oscillations of transconductance g_m with gate voltage V_{GS} for a 5-μm-gate MODFET at different magnetic fields, and $V_{DS} = 1$ mV. (Curves are displaced vertically for clarity.)

Using the SdH-M to measure C is particularly suitable for devices with high mobility because it requires a modest magnetic field to observe several oscillation peaks in a high-mobility device (the oscillation period is proportional to the inverse of magnetic field). In our experiments, only the GaAs MODFET's have sufficiently high mobility that C can be measured accurately by the SdH-M method.

IV. DETECTION OF ONSET OF PARALLEL CONDUCTION

As pointed out in the previous section, the electron density N in the channel can be determined from the oscillation period $\Delta(1/B)$, and if C is independent of gate voltage, the N versus V_{GS} curve will be a straight line. In GaAs MODFET's, when parallel conduction in the low mobility AlGaAs layer begins, C becomes a function of gate voltage, and drops with increasing gate voltage. In this case, the N versus V_{GS} curve would deviate from a straight line. The onset of parallel conduction can be determined from that deviation.

Fig. 6 shows the drain current of the 5-μm-gate-length MODFET versus magnetic field at two gate voltages. The electron density was calculated from the oscillation period $\Delta(1/B)$, and is plotted against V_{GS} in Fig. 7. It can be seen that once parallel conduction starts, the electron density in the channel almost ceases to increase with increasing V_{GS}. From the linear part of the curve, the gate-to-channel capacitance is determined to be 1.65×10^{-7} F/cm^2, which is about 15 percent smaller than that measured by the SdH-G method. This difference may be explained by the fact that the parallel conductance starts before $V_{GS} = 0$. Fig. 8 shows the N versus V_{GS} curves of another 5-μm-gate MODFET with different threshold voltage and the onset of parallel conduction. Again, the N curve bends very sharply once the parallel conduction starts.

V. THE CHANNEL-LENGTH-EFFECT ON THE SdH OSCILLATIONS

As discussed in Section II, when Landau quantization occurs, electrons travel in cyclotron orbits, and each orbit contributes a SdH oscillation peak. In long-channel MOSFET's the amplitude of the oscillation as a function of mobility V_{GS} and B has been the subject of several papers

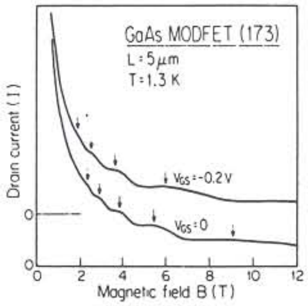

Fig. 6. The SdH oscillations of the drain current I with magnetic field B for a 5-μm-gate MODFET at different gate voltages. Arrows indicate the SdH oscillation peaks, and $V_{DS} = 1$ mV.

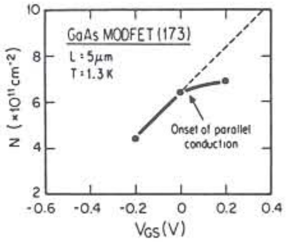

Fig. 7. The electron density N in the channel of a 5-μm-gate MODFET versus the gate voltage V_{GS}.

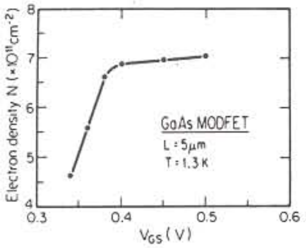

Fig. 8. The electron density N in the channel of another 5-μm-gate MODFET of different threshold voltage versus the gate voltages V_{GS}.

TABLE I
THE SdH OSCILLATION CUT-OFF LENGTH OF TWO DEVICES CALCULATED AT DIFFERENT MAGNETIC FIELDS

L_{eff} (nm)	B (T)	L_{cut} (nm)	$L_{eff} - L_{cut}$ (nm)
90	11	34.6	55.4
	14.7	35.4	54.6
80	11	26.8	53.2
	18	27	53

(e.g., [3]). However, as the cyclotron orbit diameters become comparable to the channel length, a decrease of the oscillation amplitude has been observed relative to the amplitude in long channel devices [16]. This amplitude decrease for a channel length L of 300 nm was evident for all quantum state numbers at $B = 3$ T ($d_0 = 30$ nm), and it became evident for $n \geq 3$ ($d_3 = 40$ nm) at $B = 7.9$ T. Kamgar and Tsui [16] attributed this effect to scattering of the electrons as wavefunctions overlapped the heavily doped source and drain. When this becomes a significant fraction of the total scattering that the electrons experience in the channel, the effect is equivalent to a decrease in mobility. This means that the Landau levels broaden and tend to smear together.

The channel-length-effect on the amplitude of SdH oscillation is very striking on our experiments. Two MOSFET's with channel lengths of 80 and 90 nm were used. The channel lengths were measured by an electrical method (EM) and the "closed-channel" method (CCM) [14], [15]. The g_m versus V_{GS} curves for a 90-nm-channel MOSFET, at different magnetic fields, are shown in Fig. 4. As the magnetic field was reduced from 22 T, there were four peaks observable at $B = 14.7$ T, and at $B = 11$ T, the fourth peak disappeared completely leaving only three observable peaks. For a MOSFET with an electrical channel length of 80 nm, there were two peaks at $B = 11$ T, and three peaks at 18 T. We calculated the diameter of the last observable cyclotron orbit using (2), and call it the cut-off length L_{cut}. The cut-off lengths of MOSFET's with 80- and 90-nm channel lengths at different magnetic fields are listed in Table I, which shows that for a given device the cut-off lengths at different magnetic fields are approximately the same, and are about 55 nm shorter than the electrical channel length measured by the EM and CCM methods.

To be able to extract quantitative information about the channel length from the above observations, a quantum-mechanics solution for electron transport in systems such as ours is needed. No solution exists at present, and therefore we can only confine ourselves to some qualitative remarks. It is tempting to postulate that the last observable peak corresonds to the highest order orbit that "fits" in the channel of our devices. The question then is why the difference betwen L_{cut} and the channel length as determined by other methods. Before we discuss this we must add a caveat to our observation of oscillation "disappearance." All we know is that oscillation peaks of order higher than a certain number are of the same or smaller magnitude than the noise of the data. Therefore, it is not easy to assign a definitive value to L_{cut}. For example, there may be one or more peaks that are not seen due to practical aspects of the experiment. For magnetic fields of 10–15 T, one additional peak corresponds to 5–8 nm, depending on the quantum number of the last observable peak (see (2)).

If we were to explain the difference L_{cut}–L as due to a signal-to-noise problem, we would have to invoke a very large number of additional peaks (at least 10 to 15) buried in the noise. Given the rapid decrease of the amplitude of the observable peaks with quantum number n, this explanation is rather unlikely. It then appears that L_{cut} is indeed quite close, i.e., within 5 to 10 nm, of the orbit diameter at which the electron scattering off the edges of the channel is so severe as to essentially destroy the coherence around the orbit. We can also exclude the possibility that channel edge raggedness, as suggested by Kamgar and Tsui [16], gives rise to additional scattering, effectively reducing L. Our process was specifically designed and confirmed to give extremely sharp channel edges [13], [14].

Clearly, more work, both experimental and theoretical, is necessary before the SdH channel-length-effect can yield quantitative information. At present we can only speculate that if the $L_{\text{cut}}-L$ difference is indeed constant with magnetic field, and from sample to sample, as indicated by our experiment, then L_{cut} can be used for approximate channel length determination at extremely small channel geometries.

VI. CONCLUSION

We have demonstrated that the Shubnikov–de Haas oscillations can be used to measure directly the gate-to-channel capacitance of MOSFET's and MODFET's, and to detect the onset of parallel conduction in MODFET's. In addition, it can be used to provide an approximate measure of channel length in extreme-submicrometer-channel-length MOSFET's. The theoretical background for these measurements has been discussed. The SdH measurements do not require any knowledge of device parameters, and are immune to gate parasitic capacitance and source–drain series resistance. When the magnetic field is known, the gate-to-channel capacitance can be determined from the oscillation period, the onset of parallel conductance from the gate voltage, and the cut-off channel length L_{cut} from the number of oscillation peaks.

Experimental results have shown that the gate-to-channel capacitance of Si MOSFET's, both with long-channels and sub-100-nm channels, measured by the SdH-G method agree well with C–V measurements on large-area capacitors. For GaAs MODFET's, the AlGaAs film thickness calculated from the SdH-G and the SdH-M measurements of gate-to-channel capacitance is reasonably consistent with that calibrated by the timing method. Experimental results have also shown that the onset of parallel conduction in GaAs MODFET's can be determined by the SdH method with good precision. Finally, it was shown that the difference between L_{cut} and electrical channel length is independent of magnetic field, or sample, and thus may be used as an independent measure of channel length at extreme submicrometer sizes.

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