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Gate controlled magnetoresistance in a silicon metal-oxide-semiconductor field-effect-transistor

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We present a study of the magnetoresistance (MR) of a Si metal-oxide-semiconductor field-effect-transistor (MOSFET) at the break-down regime when a magnetic field is applied perpendicular to the plane of the device. We have identified two different regimes where we observe a large and gate-voltage dependent MR. We suggest two different mechanisms which can explain the observed high MR. Moreover, we have studied how the MR of the MOSFET scales with the dimensions of the channel for gate voltages below the threshold. We observed a decrease in the MR by two orders of magnitude by reducing the dimensions of the channel from $50\times 280\ \mu m^2$ to $5\times 5\ \mu m^2$. © *2010 American Institute of Physics*. [doi:10.1063/1.3475771]

A very large magnetoresistance (MR) has been recently observed at high electric fields in nonmagnetic semiconductors and it has been attributed to the modification of the band structure by the magnetic field in Schottky barriers and tunnel junctions devices.[1–3] In other experiments, the large MR was attributed to the space charge limited transport regime.[4–6] In this work we study the MR of a Si metal-oxide-semiconductor field-effect-transistor (MOSFET) at different values of the source to drain bias V_{SD} up to the break-down regime. We identify two different mechanisms that are responsible for the high MR, depending on the value of the gate voltage V_G. For V_G above the threshold bias, where a two dimensional inversion layer connects the source and drain contacts, the saturating behavior of the MR and the dependence on the carrier concentration in the channel suggest that the MR is caused by the confinement of the hot electrons into the lowest Landau level. Below the threshold voltage, the linear and nonsaturating trend of the MR and the linear dependence with the carrier mobility suggest that space-charge effects in the bulk become important.

The different nature of the MR for gate voltages above and below the threshold is highlighted in Fig. 1(a). The MR is shown as $\{[R(B)-R(0)]/R(0)\}\times 100\%$, with the magnetic field applied perpendicularly to the plane of the device, at high V_{SD}. For V_G above the threshold gate voltage ($V_G^{th}=0.3$ V) the MR saturates at high fields, whereas we found a linear and nonsaturating field-dependence for voltages below the threshold, when no inversion layer has formed. In order to distinguish the different behavior of the MR in the two regimes we compare the break-down source-drain voltage at zero and large magnetic field up to 10 T. As it becomes obvious in Fig. 1(b), the MR at high V_{SD} values is caused by the suppression of the break-down current and this suggests a strong entanglement between the MR and the mechanisms that lead to the break-down.

Our MOSFET has a high resistivity Si-i substrate ($\rho>7000\ \Omega$ cm) oriented along the (100) direction. It is highly phosphorous doped in selected regions (at a peak concentration of 10^{20} cm^{-3}) to form Ohmic contacts. At 4.2 K, the mobility has a peak of 0.15 m^2/V s at $V_G=1$ V. When a voltage above the threshold is applied to the gate, a two dimensional conduction channel of electrons is formed. This is confirmed by the appearance of Shubnikov de Haas (SdH) oscillations at low V_{SD}, as shown in Fig. 1(c) (top). At high V_{SD}, the source and the drain of the MOSFET are pinched off, as sketched in Fig. 1(c) (bottom), so that the inversion layer only partially extends throughout the Si-channel. When a bias is applied between the source and the drain, the current is injected from the inverted part of the channel to the depleted region as in a reversed biased p-n junction. At high electric field, the conduction electrons in the inverted part of the channel gain sufficient energy to ionize the Si atoms and start an avalanche ionization process that leads into the break-down regime. All the measurements presented in this paper were taken at a temperature of 4.2 K.

When a large perpendicular magnetic field is applied, the energy spectrum of the two-dimensional (2D) inversion channel is not continuous anymore, but the carriers are confined into discrete Landau levels with one-electron energies of $E_n=\hbar\omega_c(n+1/2)$, where $\omega_c=eB/m^*$ is the cyclotron frequency and m^* is the effective electron mass. With increasing B, the spacing between the levels and the degeneracy of each level, given by $N_L(B)=eB/h$, increase as sketched in Fig. 2(a). For a magnetic field of the order of 10 T, the energy spacing between the Landau levels, $\hbar\omega_c$, is about 5.8 meV. This value is much higher than the kinetic energy gain due to the presence of the electric field in the channel (0.34 meV at $V_{SD}=19$ V) and, therefore, transitions between the Landau levels are suppressed. Moreover, for sufficiently low carrier densities $n\leq 2N_L(B)$, where we assume no removal of spin degeneracy by the magnetic field, all the hot conduction electrons occupy the lowest Landau level. At 10 T, $2N_L(B)$ is of the order of 6×10^{15} m^{-2} and this corresponds to the density of electrons in the channel for $V_G=1$ V. Therefore, at high magnetic field and for gate voltages below 1 V all the hot electrons in the channel have a kinetic energy of the order of 2.9 meV (energy of the lowest Landau level). This energy is not sufficient to ionize the Si atoms and the break-

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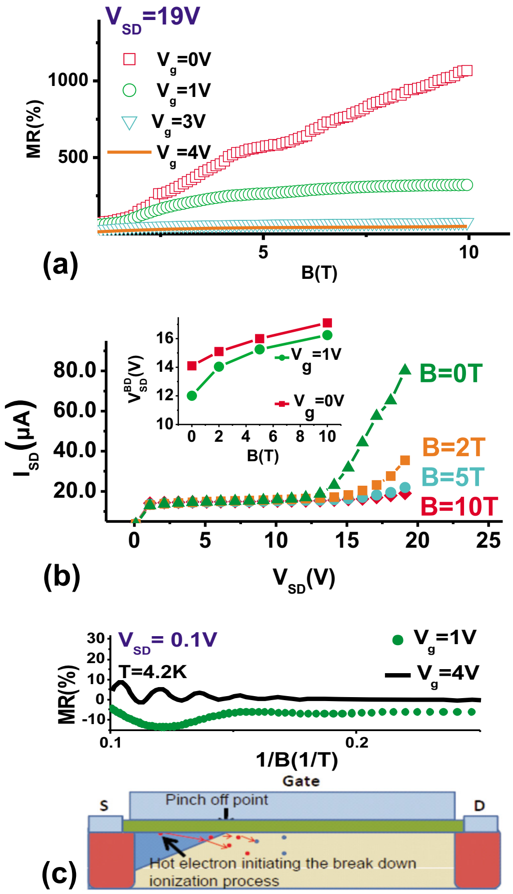

FIG. 1. (Color online) (a) MR of the MOSFET channel at different values of the gate voltage. The channel width and length are 15 and 115 μm, respectively. (b) Current vs source to drain bias graphs of the MOSFET for $V_G=1$ V at different values of the magnetic field. Inset: dependence of the break-down source to drain bias with B for $V_G=1$ V (circles) and $V_G=0$ V (squares). (c) Top: SdH oscillations measured at a source to drain bias of 100 mV for a gate voltage of 1 and 4 V. The period of the oscillations $(1/B_n-1/B_{n-1})$ depends on the density of carriers in the channel n_{2D} as $h(1/B_n-1/B_{n-1})=2e/n_{2D}$. Bottom: Schematic of the break-down regime of the MOSFET. At high values of the source to drain bias the channel is pinched off. Due to the high electric field in the channel the conduction electrons gain sufficient energy to trigger an avalanche ionization process that leads to the exponentially increasing break-down current.

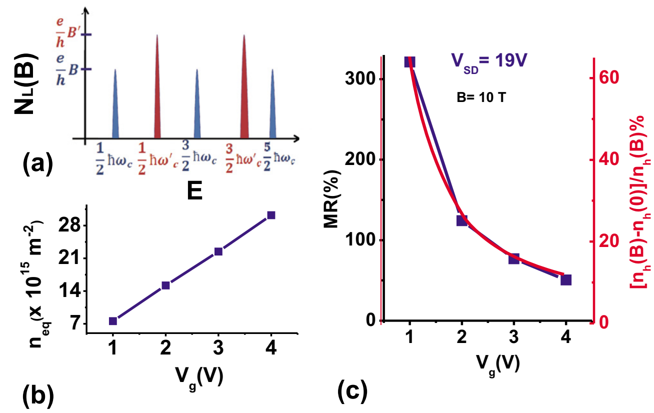

FIG. 2. (Color online) (a) Energy levels of the 2D inversion channel in the presence of a magnetic field. As the value of the field is increased from B to B′, the spacing between the levels and the degeneracy of each level increase. (b) Density of carriers in the conductive channel as a function of the gate voltage deduced from the period of the SdH oscillations at $V_{SD}=0.1$ V. (c) Dependence of the MR on V_G at B=10 and $V_{SD}=19$ V (bullets) and estimated variation of the hot conduction electrons in the channel (continuous line).

down current is suppressed. When the density of electrons in the channel increases above 6×10^{15} m^{-2} (V_G above 1 V), we need to take into account the occupation of higher Landau levels. Figure 2(c) shows the MR with respect to V_G (blue bullets). It is interesting to note that it follows the same trend of the relative variation in the hot electron concentration in the channel as a function of V_G when a magnetic field is applied (continuous red line). This has been calculated by assuming that the break-down current is only triggered by the most energetic electrons that occupy higher Landau levels and can be written in terms of V_G as $\Delta n/n_h^B=[(h/eB)aV_G-1]^{-1}$, where a is the proportionality factor between n_h^0 and V_G [gradient of the line in Fig. 2(b)]. This further confirms that the suppression of the break-down current by the magnetic field is caused by the condensation of the hot electrons into the lowest Landau level.

At $V_G=0$ the situation is different as no quasi 2D inversion channel is formed. In this case the avalanche ionization process is not initiated by the hot electrons in the 2D inversion layer but by electrons which gain sufficient energy due to the strong electric field between the two Ohmic source and drain contacts. Recently, a non saturating MR has been observed in bulk silicon by Delmo *et al.*[4] when a very high electric field was applied. In this case, the MR has been associated with the space charge transport regime, when the injected carrier concentration is much larger than the equilibrium concentration in the bulk material.[12,13] In this regime, the inhomogeneities of the electric field along the channel is responsible for the noncompensation of the Hall currents that leads to the MR. The nonsaturating MR has been found to be common to many nonmagnetic disordered materials, such as inhomogeneous semiconductors with metallic inclusions[8,9] and in doped silver chalcogenides.[10,11] Parish *et al.*[7] have proposed a model that explains the nonsaturating MR in the strongly inhomogeneous systems and predicted a linear dependence of the MR with the mobility of carriers when $\Delta\mu/\mu<1$, where $\Delta\mu$ is the width of the mobility disorder. In order to verify this, we have repeated the same set of measurements in a MOSFET with the gate designed to allow Hall measurements of the carrier mobility in the channel. In this case the substrate was slightly boron doped. At high source to drain biases $n_{inj}/n_{eq}=1.2$ [refer to Fig. 3(a)]. The concentration of the injected electrons, n_{inj}, is thus larger than the equilibrium concentration of carriers in silicon, n_{eq}, as expected in the space charge transport regime.[5] Moreover, in Fig. 3(a) we report the current versus V_{SD} at zero gate voltage and magnetic field in a log-log scale. We see that the current does not follow the Ohmic curve, but depends on a higher power of V_{SD}, as expected for this transport regime in the most general case, when traps are present in the channel.[12] Figure 3(b) shows that the MR is nonsaturating for $V_G=0$, similarly to what we obtained in the undoped FET devices at $V_G<V_G^{th}$. We have measured the mobility of carriers in the channel and the MR at different temperatures, ranging from 4.2 K to room temperature. In accordance with Parish we find a linear dependence of the MR with the mobility, as shown in Fig. 3(c). We therefore conclude that for $V_G<V_G^{th}$ the MR can be explained with the inhomogeneity of the electric field along the channel associated with the space charge transport regime.

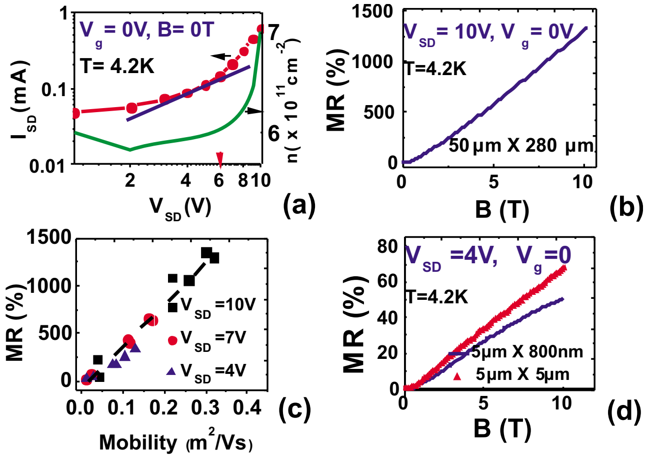

FIG. 3. (Color online) (a) Left axis: current vs source to drain bias at zero magnetic field measured in the $50\times 280\ \mu\text{m}^2$ slightly doped device. The continuous blue line represents the $I\propto V$ Ohmic line. Right axis: Hall measurements of the carriers concentration in the channel as a function of the source to drain bias. The break-down source to drain potential is indicated by a red arrow. (b) MR vs B curves measured at $V_G=0$ V in the $50\times 280\ \mu\text{m}^2$ devices. (c) MR of the MOSFET with a slightly doped boron substrate as a function of the mobility of carriers in the channel for $V_{SD}=10$ V, 7 V, 4 V, and $V_G=0$ V. The width and length of the channel are 50 μm and 280 μm, respectively. The graph has been obtained by taking Hall measurements of the mobility and MR measurements at different temperatures from 4.2 K to room temperature. (d) MR vs B curves measured at $V_G=0$ V in the $5\times 5\ \mu\text{m}^2$ and $5000\times 800\ \text{nm}^2$ slightly doped devices.

We finally compare the MR in devices with different channel dimensions but patterned from the same wafer. It has been previously suggested by Delmo *et al.*[4] that the large MR can also be obtained in smaller devices, if the high mobility and low equilibrium carrier concentration conditions are satisfied, as long as the electrons remain correlated. So far, only large devices of $5\times 5\ \text{mm}^2$ were studied in literature. The MR curve of the largest device we investigated ($50\times 280\ \mu\text{m}^2$) is shown in Fig. 3(b) at $V_{SD}=10$ V. This can be compared with the MR curves of two smaller devices with channel dimensions of $5\times 5\ \mu\text{m}^2$ and $5000\times 800\ \text{nm}^2$, shown in Fig. 3(d). The MR is two orders of magnitude lower in the smaller devices, even though the value of the effective electric field applied between the source and the drain is two orders of magnitude larger. By reducing only the channel width of the device from 5 μm to 800 nm the MR further drops by a factor of two (at 10 T). In our opinion, in order to understand the strong suppression of the MR with the reduction in the channel dimensions, two critical lengths should be considered: the cyclotron radius, $D_c=m^*v/qB$, and the screening length (Debye length). The first quantity accounts for the orbital origin of the MR but is of the order of a few tenths of nm's and thus much smaller than the channel dimensions. The screening length, on the other hand, is of the order of a few micrometers. We suggest that when the channel dimensions are of the same order of magnitude of the screening length the Mott–Gurney regime is not established. In order to justify this, however, more measurements with a wider range of devices with different dimensions are required.

In conclusion, we have measured the MR in the channel of a silicon MOSFET at high values of the source to drain bias and for different gate voltages. We have observed that, depending on the gate voltage, the mechanisms that cause high MR are of different nature: for gate voltages above the threshold the MR is caused by the confinement of the hot electrons in the lowest Landau level, whereas for voltages below the threshold the MR has to be associated with the space charge transport regime. We also studied how the MR drops down with the dimensions of the channel for gate voltages below the threshold and found a decrease of two orders of magnitude when the channel size is decreased from 50×280 to $5\times 5\ \mu\text{m}^2$.

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