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Monte Carlo simulation of Hall and magnetoresistance mobility in SOI devices

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Abstract

We simulate the electron transport in the inversion layer of ultra-thin silicon-on-insulator devices in the presence of a perpendicular magnetic field. We compute and compare the Hall mobility, the magnetoresistance mobility and the low-field drift mobility. The Hall and magnetoresistance factors, which are essential in order to have precise information on the effective mobility from experimental Hall or magnetoresistance data, are computed for various ultrathin SOI structures and temperatures. The results show that Hall mobility and magnetoresistance mobility are modulated by the SOI size effects, in particular the subband splitting. Not only the Hall and magnetoresistance factors can be quite different from unity, but they also depend on the device geometry and operating conditions.

Keywords: Electron mobility; Geometric magnetoresistance; Hall mobility; SOI; Monte Carlo

1. Introduction

Carrier mobility in a metal–oxide–semiconductor field-effect transistor (MOSFET) is a key parameter which has a strong impact on device performance, even in the quasi-ballistic case [1]. For this reason, it is very important to determine with very high accuracy not only the mobility value in a given device, but also its behavior and dependence on device structure, material, technology process, etc. Thus, the SIA Roadmap, for example, links the success in the device scaling down trends to the search for approaches that increase carrier mobility [2].

However, common mobility extraction techniques such as split *C–V* [3] and static parameter extraction [4] are not well suited to the analysis of very short channel devices in the deep sub-micron regime, since they strongly depend on precise measurement of the effective channel length and can be affected by oxide/interfacial charges. An inaccurate determination of the channel length leads to a wrong estimation of carrier mobility. Other techniques based on carrier transport properties in the presence of a magnetic field, such as Hall or geometric magnetoresistance (MR) [5,6] measurements do not need precise determination of the channel length and can be used to determine carrier mobility even at a very low inversion charge concentration (subthreshold regime). To cite some examples, Hall mobility extraction has been compared to other mobility extraction methods in double-gate silicon-on-insulator (SOI) devices in [7]. Magnetoresistance techniques have allowed the study of mobility dependence on channel length in bulk silicon MOSFETs and SOI devices for a wide range of inversion charge, from deep weak inversion to strong inversion [8–10], and also the analysis of ballistic and pocket effects on the mobility of very short channel devices [11,12]. From a theoretical point of view, i.e., from their definitions, both Hall mobility and MR mobility are in principle different parameters from effective drift mobility. The expressions

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for effective drift mobility, Hall mobility and MR mobility in the relaxation time approximation read [9]:

$$\mu_{\mathrm{eff}} = \frac{e}{m^*} \frac{\int_0^\infty EN(E)\tau_{\mathrm{m}}(E)\left(-\frac{\partial f}{\partial E}\right)\mathrm{d}E}{\int_0^\infty N(E)f(E)\mathrm{d}E}, \tag{1}$$

$$\mu_{\mathrm{H}} = \frac{e}{m^*} \frac{\int_0^\infty EN(E)\tau_{\mathrm{m}}(E)^2\left(-\frac{\partial f}{\partial E}\right)\mathrm{d}E}{\int_0^\infty EN(E)\tau_{\mathrm{m}}(E)\left(-\frac{\partial f}{\partial E}\right)\mathrm{d}E} \tag{2}$$

and

$$\mu_{\mathrm{MR}} = \frac{e}{m^*} \sqrt{\frac{\int_0^\infty EN(E)\tau_{\mathrm{m}}(E)^3\left(-\frac{\partial f}{\partial E}\right)\mathrm{d}E}{\int_0^\infty EN(E)\tau_{\mathrm{m}}(E)\left(-\frac{\partial f}{\partial E}\right)\mathrm{d}E}}, \tag{3}$$

where $f(E)$ is the Fermi–Dirac distribution, $N(E)$ the density of states, $\tau_{\mathrm{m}}(E)$ the energy-dependent momentum relaxation time, e the electron charge, and m^* the electron effective mass.

However, there are some particular circumstances where the three parameters coincide, for example, on the assumption of mono-energetic carriers, that is to say, when all carriers are assumed to have the same energy. In fact, the opposite is the case: these quantities are generally different so that the mobility determined by these techniques cannot be directly identified with the drift effective mobility. This being so, that the Hall mobility, μ_{H}, is related to the drift effective mobility μ_{eff} through the Hall factor r_{H}:

$$\mu_{\mathrm{H}} = r_{\mathrm{H}}\mu_{\mathrm{eff}} \tag{4}$$

and the magnetoresistance mobility, μ_{MR}, is related to the drift effective mobility μ_{eff} through the magnetoresistance factor r_{MR}:

$$\mu_{\mathrm{MR}} = r_{\mathrm{MR}}\mu_{\mathrm{eff}}. \tag{5}$$

Therefore, we would need to know a priori r_{H} and r_{MR} in order to determine the effective mobility μ_{eff} from μ_{MR} and μ_{H}.

Extensive work has been done on bulk semiconductors and 3D transport, including Monte Carlo simulations [13]; Hall factor and MR factor have been studied and characterized as functions of the scattering mechanisms involved in the transport [14,15] in bulk semiconductors at different temperatures. The typical values of these coefficients for Coulomb and phonon scattering in bulk silicon are listed in Table 1, for low magnetic field; in the limit of high magnetic field, instead, r_{H} and r_{MR} tend to 1 irrespective of the prevalent scattering mechanism [14]. However in a 2D inversion layer, the situation is different and no precise results are known for the Hall and MR factors.

Table 1
Hall and MR factors for low magnetic field in bulk silicon

Scattering mechanisms	Hall factor	MR factor
Acoustic phonon	1.18	1.33
Coulomb scattering	1.93	2.43

The fact that the Hall, magnetoresistance and drift mobilities differ is well documented in the literature. Our aim is to quantify this difference for the particular case of ultra-thin SOI structures with subband splitting and multiple scattering mechanisms. The goal is to nourish the correlation of experimental data obtained from these three types of measurements.

The purpose of this paper is, therefore, to study how carrier transport is affected by the presence of a magnetic field in ultra-thin SOI devices and to compute the Hall and MR factors for different devices and conditions. We start by summarizing how Hall and MR mobilities are defined and measured, and how they can be numerically computed. We employ Monte Carlo simulations to study electron transport with a magnetic field perpendicular to the transport plane: Hall, MR and effective mobilities are calculated for different SOI device structures at different temperatures and the corresponding Hall and MR factors are computed.

2. Carrier transport in the presence of a magnetic field

The Hall effect is a well-known phenomenon that occurs when carriers move in the presence of a magnetic field perpendicular to the transport plane. The conventional theory is developed considering a rectangular device longer than it is wide. While the carrier motion is deflected by the Lorentz force, there cannot be any current in the transversal direction. Indeed the Lorentz force is balanced, on the average, by an electric field in the transversal direction. The corresponding Hall voltage V_{H} can be experimentally measured, and used to compute the Hall mobility μ_{H} through [6]:

$$\mu_{\mathrm{H}} = \frac{V_{\mathrm{H}}}{R_{\square}BI_x}, \tag{6}$$

where $R_{\square}$ is the sheet resistance, B the magnetic field, I_x the device current. To extract the Hall mobility from the simulation data, an equivalent expression will be used, where μ_{H} is obtained from the Hall angle θ_{H}, that is the angle between the current direction (the x axis in this case) and the total electric field (drift plus Hall field) [15]:

$$\mu_{\mathrm{H}} = \frac{1}{B}\tan\theta_{\mathrm{H}} = \frac{E_y}{E_xB}. \tag{7}$$

The Hall mobility is related to the drift effective mobility μ_{eff} through the Hall factor r_{H} defined in Eq. (4). If the carriers are assumed to be mono-kinetic, this factor reduces to unity and the two quantities, μ_{H} and μ_{eff} coincide; when the carrier energy distribution is taken into consideration, r_{H} no longer equals one. An expression for r_{H} can be obtained in the relaxation time approximation, and involves the scattering rates dependence on energy for the different scattering mechanisms [15].

If the device is short and wide, the lateral field is short-circuited because of the contacts. In this case, a geometric