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An analytical model for the electron effective mobility in a strained silicon inversion layer☆

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ABSTRACT

An electron effective mobility analytical model without empirical parameters is investigated for the strained silicon inversion layer, which can be conveniently applied by device and circuit designers. Four kinds of scattering mechanisms, i.e., coulomb scattering, acoustic phonon scattering, intervalley phonon scattering and surface roughness scattering, are taken into account to calculate the electron mobility for the 2D (two-dimensional) inversion layer through a one-dimensional inverse transform. Considering the quantum confinement and strain effect, the valley electron occupancy variation is dissected. In regard to the Si/(001)$Si_{1-x}Ge_x$ and Si/(110)$Si_{1-x}Ge_x$ Si common orientation, the dependence of the electron effective mobility with various Ge content on the inversion charge density is analyzed in detail, and by means of this the mechanism of the mobility enhancement under different situations and the mobility saturation are brought to light.

1. Introduction

Mobility enhancement is an attractive option, because it can potentially improve device performance beyond any of the benefits from device scaling [1]. Strained silicon (S-Si) technology is one of the most advanced technologies in microelectronics, with the advantages of high-mobility, adjustable energy-band structure and compatible processing technology compared with traditional silicon [2]. Carrier mobility with enhancement factor up to 1.8 is achieved for an *n*-channel devices[3]. MOSFET (metal-oxide-semiconductor field-effect transistor) performance improvements are continuing via strained channels, which are being adopted in nearly all 90, 65, and 45 nm logic, communication, and consumer technologies [4]. For high speed and energy efficient applications, Weber et al. presented a 14 nm device platform using strain-engineered FDSOI (fully depleted silicon on insulator) transistors [5]. Intrinsically strained channel techniques are by far the most efficient, with almost 100% of the stress maintained in the channel for long active region length values [6].

Empirical equations for the electron mobility can be used easily for engineering applications, but the physical significance is not clear. A semi-empirical equation is a compromise between easy use and physical significance. Both empirical and semi-empirical methods have parameters which need to be extracted from the actual device. Therefore, their universality are often questioned. The Monte Carlo method, which has a high degree of accuracy, is exploited by researchers to study accurately the inversion electron scattering mechanism. However, this method is too complicated and time consuming, and is hard to embed in the device simulation software, so that it cannot be used in the simulation of the actual circuit. Especially, it is not straightforward for the device and circuit

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designer. The analytical models derived in this paper have the most clear physical significance, which feature simplicity, versatility, and ease of use, so that they can effectively help designers to design, modify and optimize the devices and circuits. The models can also be easily used to calculate the inversion layer electron mobility of an arbitrarily crystal plane with an arbitrarily orientation if the parameters are correctly chosen.

Using the research of mobility on strained Si material for reference, the inversion layer electron effective mobility of biaxial strained Si, by growing a layer of Si on $Si_{1-x}Ge_x$, is investigated in this paper. The rest of the paper is organized as follows. Both quantum confinement and the strain effect influence the inversion electron energy, which are the basis of scattering rate models. They are introduced in Section 2. The scattering rates are the key to calculating the mobility according to the mobility formula $\mu = q\tau/m_c$ (m_c indicates the conductive effective mass, and τ indicates the momentum relaxation time, i.e., the reciprocal of the scattering rate). Based on the energy band, the scattering rate models are built in Section 3. Then, the mobility of the common orientations for the common planes (100) and (110) is calculated and simulated in Section 4. Finally, a brief conclusion is drawn in the last section.

2. Quantum confinement and the strain effect

Different from the bulk material, carriers are 2D (two-dimensional) electron/hole gases in the normal inversion operation mode. Two new features must be considered for the carrier transport: 1) electric confinement—also referred to as quantum confinement, and 2) semiconductor-oxide interface scattering, i.e., surface roughness scattering [7].

Due to quantum confinement, the motion of carriers in MOSFET channels is restricted in the gate direction (z direction) and quantized, leaving only a 2D k vector which still characterizes the Bloch wave motion in a plane ($x - y$ plane) normal to the confining potential[7]. An energy band which extends in the k_z direction in bulk materials is now split into a series of subbands. And the six equivalent energy valleys in the bulk materials split into Δ_2 and Δ_4 due to quantum confinement, which reduces the crystal symmetry. The properties of the subbands and transport properties of the inversion and accumulation layers at the semiconductor-insulator interfaces have been reviewed in detail in Ref. [8].

In the triangular potential well approximation, the potential is given by [7]

$$V(z) = \begin{cases} qzE_{\text{eff}} & z > 0, \\ \infty & z \le 0, \end{cases} \tag{1}$$

where q stands for the electronic charge and E_{eff} stands for the effective electric field along the z direction. By matching the boundary conditions, the subband energies E_{ni} are [7]

$$E_{\text{ni}} = r_{\text{n}}\left(\frac{\hbar^2}{2m_z}\right)^{1/3}(qE_{\text{eff}})^{2/3}, \tag{2}$$

where $\hbar$ is Planck's constant over 2π, m_z is the effective mass in the z direction, r_n are the roots for the equation $A(-r) = 0$: $r_0 = 2.338$, $r_1 = 4.087$, $r_2 = 5.520$, $r_3 = 6.787$, $r_4 = 7.944$, ..., and $A(-r)$ is the Airy function.

At the same time, strain also makes the band structure change. So, for the strained Si inversion layer, the band structure depends on both the quantum confinement and strain splitting. Strain effects in MOSFETs are determined by the coactions of the electric confinement and strain effect. First, quantum confinement and strain splitting can be additive or subtractive. Second, strain alters the in-plane 2D band structures, leading to changes of both the conductivity and density of state (DOS) effective masses [7]. The shift in energies of the conduction band valleys owing to the strain effect can be calculated by deformation potential theory. And the effective mass change owing to the strain effect can be calculated by K·P perturbation theory, which is presented thoroughly in Ref. [9].

3. Scattering models

There are many reasons why the transport properties of the electron gas in a silicon MOS inversion layer should be treated as a two-dimensional electron gas (2DEG) [10], where the motion perpendicular to the surface is quantized, instead of a 3DEG [11], even at room temperature. In the NMOSFET inversion layer, except for ionized impurity scattering, acoustic phonon intravalley scattering and intervalley scattering, surface roughness scattering must be included, as the introduction above said. The various scattering rates based on 2DEG transport theories are as follows:

With respect to the scattering potential, we use a screened coulomb potential function, which is written as the following formula:

$$V(r) = \frac{-q^2}{4\pi\bar{\mathcal{E}}r}\exp(-f_{\text{sc}}r), \tag{3}$$

where $\bar{\mathcal{E}}$ is the average permittivity,

$$\bar{\mathcal{E}} = \frac{\mathcal{E}_{\text{si}} + \mathcal{E}_{\text{ox}}}{2}, \tag{4}$$

$\mathcal{E}_{Si}$ denotes the permittivity of Si and $\mathcal{E}_{ox}$ denotes the permittivity of SiO_2. The screening wave vector, f_{sc}, is given as the inverse of the Debye length for semiconductors [12]:

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