Solid-State Electronics 94 (2014) 23–27

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Optimization of uniaxial stress for high electron mobility on biaxially-strained n-MOSFETs

Wookyung Sun, Hyungsoon Shin *

Dept. of Electronics Engineering, Ewha Womans University, 11-1 Daehyun-Dong, Seodaemoon-Gu, Seoul 120-750, Republic of Korea

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 23 December 2013
Accepted 22 January 2014
Available online 12 February 2014

The review of this paper was arranged by Prof. A. Zaslavsky

Keywords:
Strained Si
Electron mobility
Uniaxial strain
Biaxial strain
Stress

ABSTRACT

The uniaxial stress effect for high electron mobility on biaxially-strained n-MOSFET is investigated by using a one-dimensional self-consistent Schrödinger–Poisson solver. The electron mobility model includes Coulomb, intravalley phonon, intervalley phonon, and surface roughness scattering. We have found that the uniaxial stress effect on biaxially-strained n-MOSFET is significantly different from the uniaxial stress effect on unstrained Si n-MOSFET. It is well known that longitudinal and transverse tensile uniaxial stresses are advantageous for strain-induced high electron mobility. However, we found that the uniaxial strain condition for electron mobility enhancement is changed when it is applied to the biaxially-strained n-MOSFET. To optimize the combined effect of uniaxial and biaxial strain, the longitudinal tensile and transverse compressive uniaxial stresses are advantageous and vertical stress is not helpful for biaxially-strained n-MOSFET.

1. Introduction

Strained-Si technology by applying biaxial stress is an important technology to improve the performance of CMOS devices and it has been studied by a large number of researchers for several decades [1–7]. Strain enhances the electron mobility by reducing the conductivity effective mass and the scattering rate. However, it has been reported that the strain induced mobility enhancement in s-Si nMOSFETs decreases with reducing the gate length [8–10]. Thus, it is necessary to combine different stressors for short channel devices and several research groups have reported that the carrier mobility can be significantly enhanced by combining uniaxial strain and biaxial strain [11,12]. Furthermore, a combination of uniaxial and biaxial strain may appear when Multi-Gate MOSFET transistors are fabricated on strained SOI wafers [13,14]. However, there is a lack of research on the electron mobility enhancement induced by combining uniaxial and biaxial strain.

The aim of this letter is the optimization of uniaxial strain for biaxially-strained nMOSFETs. This paper is organized as follows. Sections 2 and 3 present the models for electron mobility and stress effects. In Section 4, the results of our simulation are presented and analyzed, and Section 5 reports the discussions and conclusions.

2. Mobility calculation

We calculated the wave functions using our Schrödinger–Poisson solver. The total mobility has been analyzed by means of numerical simulations. The relaxation times for Coulomb, phonon, and surface-roughness scattering are considered using the equation described in [15–18].

The traditional theory of intravalley and intervalley phonon scattering has already been developed and expressions for the momentum relaxation rate have been obtained. The momentum relaxation rate for deformation potential scattering by intravalley acoustic phonons (τ^i_{intra}) from the ith subband to the jth subband is given by

$$\frac{1}{\tau^i_{intra}(E)} = \sum_j \frac{n_i^{ac} m_{d,j} D_{ac}^2 k_B T}{\hbar^3 \rho s_l^2} F_{i,j} U(E - E_j), \tag{1}$$

$$F_{i,j} = \int_{-\infty}^{+\infty} |\xi_i(z)|^2 |\xi_j(z)|^2 \, dz, \tag{2}$$

where n_i^{ac} is the degeneracy of the valley with respect to intravalley scattering, $m_{d,j}$ is the density-of-state effective mass of electrons at the jth subband, D_{ac} is the intravalley deformation potential for acoustic phonon scattering, ρ is the mass density of the crystal, s_l is the longitudinal sound velocity, and $U(x)$ is the Heaviside step function. $F_{i,j}$ is the form factor determined by the wave functions of the ith and the jth subbands [16].

* Corresponding author. Tel.: +82 2 3277 2595; fax: +82 2 3277 3494.
E-mail address: hsshin@ewha.ac.kr (H. Shin).

http://dx.doi.org/10.1016/j.sse.2014.01.005
0038-1101/

The momentum relaxation rate for intervalley phonon scattering (τ^i_{inter}) from the ith subband to the jth subband is given by:

$$\frac{1}{\tau^i_{inter}(E)} = \sum_j \left\{ \sum_k^{\{f,g\}} \frac{n_{ij}^{f,g} m_{d,j} D_k^2}{\hbar \rho E_k} F_{i,j} \left(N_k + \frac{1}{2} \pm \frac{1}{2} \right) \cdot \frac{1 - f(E \mp E_k)}{1 - f(E)} U(E \mp E_k - E_j) \right\}, \tag{3}$$

where k is the index of phonons and $n_{ij}^{f,g}$ is the degeneracy of the valley j undergoing an intervalley transition from valley i to valley j, D_k is the deformation potential of the kth intervalley phonon, E_k is the energy of the kth intervalley phonon, N_k is the Bose–Einstein distribution function, and $f(E)$ is the Fermi–Dirac distribution function. In (3), f and g are the type of intervalley scattering. The upper or lower sign must be taken for the process of emission and absorption of phonons, respectively [14]. The physical parameters used in equations are listed in Table 1.

For silicon, intervalley phonon energy (E_k) depends on f type and g type scattering mechanisms and we used E_k parameter set proposed by Ferry [17]. In case of D_{ac}, various D_{ac} parameter sets are used to represent the experimental mobility. In addition, some of them suggest that the effective deformation potential should be dependent on surface-field [18,19]. Thus, in order to more accurately calculate the μ_{ph}, we use the concept of effective deformation potential which means the deformation potential is changed by effective electric field (E_{eff}). In this work, the effective intravalley deformation potential ($D_{ac,eff}$) and effective intervalley deformation potential ($D_{k,eff}$) are modeled as:

$$D_{ac,eff}(E_{eff}) = A + B(E_{eff})^{0.3}, \tag{4}$$

$$D_{k,eff}(E_{eff}) = D_k \cdot \frac{D_{ac,eff}(E_{eff})}{D_{ac}}, \tag{5}$$

where E_{eff} is the effective electric field, A and B are fitting parameters, D_{ac} and D_k are deformation potentials at E_{eff} = 0.1 MV/cm. The value of exponential (=0.3) is theoretically equal to electric field dependence of carrier mobility on a (100) surface [16]. The fitting parameters have been chosen by comparing calculated data with experimental data. The fitting parameters A and B are determined from two limits that $D_{ac,eff}$ at E_{eff} = 0.1 MV/cm is 9 eV and $D_{ac,eff}$ at 1 MV/cm is 12 eV, and we used A = 5.986, B = 0.095 for a (100)/⟨110⟩ nMOSFETs. Fig. 1 shows the relationship between the calculated μ_{ph} and E_{eff} for $N_{sub} = 2 \times 10^{16}$ cm^{-3}. As shown in Fig. 1, the slope of the μ_{ph} calculated under the constant deformation potential [16] is different from experimental values, whereas, the μ_{ph} calculated using the effective deformation potential as shown in (4) and (5), gives substantially better agreement with the experimental data.

Table 1
Physical parameters used in mobility calculation.

Symbol	Value	Definition
E_k	59 meV	Energy of f type intervalley
	63 meV	Energy of g type intervalley
$n^{ac}_{\Delta 2}$	2	Degeneracy number of each valley
$n^{ac}_{\Delta 4}$	1	For intravalley scattering
$n^{f}_{\Delta 2\Delta 4}$	4	
$n^{f}_{\Delta 4\Delta 2}$	2	Degeneracy number of each valley
$n^{f}_{\Delta 4\Delta 4}$	2	For intravalley scattering
$n^{g}_{\Delta 4\Delta 4}$	1	
ρ	2329 kg/m^3	Crystal mass density
s_l	9037 m/s	Longitudinal sound velocity
m_0	9.11×10^{-31} kg	Free electron mass
ε_0	8.854×10^{-14} F/cm	Permittivity of free space
ε_{si}	11.8	Relative permittivity of Si
$m_{c\Delta 2}$	$0.19m_0$	Conductivity mass of $\Delta 2$ valley
$m_{c\Delta 4}$	$0.315m_0$	Conductivity mass of $\Delta 4$ valley
$m_{d\Delta 2}$	$0.19m_0$	Density of state mass of $\Delta 2$ valley
$m_{d\Delta 4}$	$0.417m_0$	Density of state mass of $\Delta 4$ valley
$m_{z\Delta 2}$	$0.916m_0$	Quantization mass of $\Delta 2$ valley
$m_{z\Delta 4}$	$0.19m_0$	Quantization mass of $\Delta 4$ valley
D_{ac}	9 eV	Intravalley deformation potential at E_{eff} = 0.1 MV/cm
D_k	8×10^8 eV/cm	Intervalley deformation potential at E_{eff} = 0.1 MV/cm

The total relaxation rate (τ), the electron mobility in the ith subband (μ^i) and total electron mobility (μ_{total}) are given by [16,22]:

$$\frac{1}{\tau^i} = \frac{1}{\tau^i_{Coulomb}} + \frac{1}{\tau^i_{intra}} + \frac{1}{\tau^i_{inter}} + \frac{1}{\tau^i_{surface}}. \tag{8}$$

$$\mu^i = \frac{q \int_{E_i}^{\infty} (E - E_i) \tau^i (-\partial f / \partial E) dE}{m_{c,i} \int_{E_i}^{\infty} (E - E_i)(-\partial f / \partial E) dE}, \tag{9}$$

$$\mu_{total} = \frac{\sum_i (\mu^i N_i)}{N_S}, \tag{10}$$

where $m_{c,i}$ is the conductivity mass of ith subband. In Eq. (10), N_i is the carrier density of the ith subband, and N_s is the total carrier density.

The momentum-relaxation rate for Coulomb scattering is given by [15]:

$$\frac{1}{\tau_{Coulomb}} = \frac{N_I q^4 \left[\ln(1+\gamma^2) - \frac{\gamma^2}{1+\gamma^2} \right]}{16\sqrt{2m_c}\pi \varepsilon_{si}^2 \varepsilon_0^2 E^{3/2}}, \gamma^2 = \frac{8 m_c L_D^2 E}{\hbar^2} \tag{6}$$

where N_I is the number of impurities, ε_0 is the permittivity of free space, and ε_{si} is the relative permittivity of Si, and L_D is the Debye length. The traditional theory of interface roughness scattering has already been developed and expressions for that are given by [20]. However, we neglect the screening effect and the momentum-relaxation rate for interface roughness scattering can be approximated by [21]:

$$\frac{1}{\tau_{surface}} = \frac{\pi m_d \left[\Delta \Lambda q E_{eff} \right]^2}{\hbar^3}, \tag{7}$$

where Δ is the root-mean-square height of interface roughness and Λ is the lateral decay length of interface roughness.

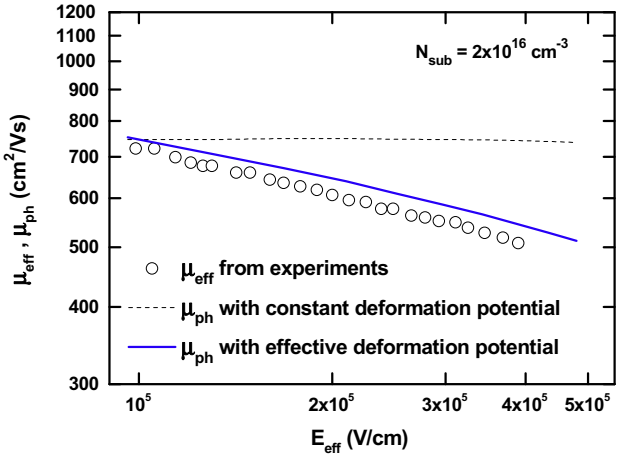

Fig. 1. E_{eff} dependence of μ_{eff} and μ_{ph} in a (100) bulk Si nMOSFETs. The open circles: experimental results taken from [16]. The dashed lines: calculated μ_{ph} using the constant deformation potential, solid lines: calculated μ_{ph} using our effective deformation potential.