Analysis of Strained-Si Device including Quantum Effect

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Strained-Si technologies are actively discussed from both sides of experiments and simulations in recent years [1, 2]. And with progressive technology scaling, quantum transport also becomes important increasingly. We linked the first principle band calculation program to the FUJITSU ensemble full band Monte Carlo simulator FALCON directly, which enables to take in arbitrary biaxial strained-Si band structure easily. And also the quantum effect was implemented by Bohm potential method [3].

The outline of a simulation is shown in Fig. 1 and 2. The DG MOSFET structure used for analysis is shown in Fig.3. The channel region is assumed to be intrinsic. Fig.4 shows electron density distribution calculated by Bohm potential method as a parameter of SOI thickness. It agrees quit well with Schrödinger-Poisson method. Fig.5 is the I_d-V_d characteristics of 40nm gate length device by classical and quantum model for x=0(unstrained) and x=0.3(strained) Ge content of $Si_{1-x}Ge_x$ buffer layer.

Next, we describe the influence of scattering. First, we compare classical and quantum model. Fig. 6 is the comparison of the scattering events for each transport model. For phonon scattering, carriers are less scattered in quantum model. Because in Bohm potential method, the sub-band energies of each valley are taken into account, the probability of inter-valley scattering decreases. For impurity scattering, the number of scattering events increases in quantum model. It is because the screening effect becomes weaker by the great reduction of electron density and it becomes easy to be scattered. For surface roughness scattering, the scattering probability decreases dramatically in quantum model. It is because the peak of carrier density is apart from an interface and the interaction between carriers and surface decreases. Second we describe the influences of strain to scattering. Fig.7 shows the number of scattering events for different Ge content. In strained-Si, valley splitting occurs and carriers gather into low energy 2-fold valley. So, inter-valley phonon scattering decreases with increasing Ge content. For impurity scattering, the scattering probability decreased slightly because the screening effect becomes stronger as carrier density in channel region increases with strain. For surface roughness scattering, the scattering probability increases since the more Ge content increases, the peak of carriers approaches an interface and carriers are mostly distributed to 2-fold valley with heavy effective mass perpendicular to an interface as shown in Fig. 8. But the velocity also increases with strain simultaneously. Hence, the number of scattering events becomes fewer.

Finally, we describe the perspective in future scaling. Fig.9 shows the ballistic rate of classical and quantum model with scaling. Quantum model enhances ballistic nature due to the reduction of surface roughness scattering. However the difference becomes small with scaling. Fig. 10 shows strained-Si is easy to be ballistic. It is because every scattering element decreases when strain is applied as shown in Fig.7. And the effect is effective even if scaling goes on. The improvement rate of current is shown in Fig. 11. Up to about 10nm of gate length, strain effect decreases with scaling. Because the channel length becomes shorter, carriers are not accelerated enough in source side channel as shown in Fig. 12. On the contrary, as is shown in Fig. 10, ballistic particles exceed the half below a 10nm regime. So the increase of the injection velocity by strain at the source edge leads also to the increase of the improvement of current again.

The strained-Si device including quantum effect was examined. The strain effect decreases with scaling to 10nm gate length regime. However, in the domain which ballistic particle is majority, the effect of strain becomes useful again by the increase of the velocity by strain at the source region. This becomes more remarkable when quantum effect is taken into account.

[1] K. Rim et al., IEDM, pp.311-314, 2003.
[2] F. M. Bufler et al., IEEE TED, vol.50, pp.278-284, 2003.
[3] B. Wu et al., IWCE-9, pp.42-43, 2003.

A full journal publication of this work will be published in the Journal of Computational Electronics.

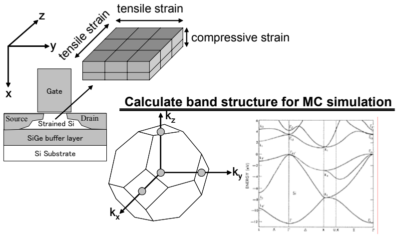
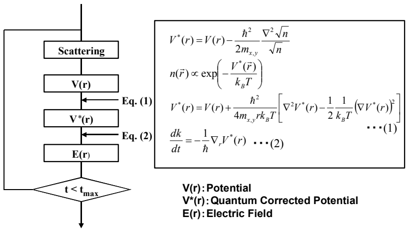


Fig.1. Fundamental strained-Si calculation methodology. Band calculation of strained-Si is needed for MC simulation



$$V^*(r) = V(r) - \frac{\hbar^2}{2m_{x,y}} \frac{\nabla^2\sqrt{n}}{\sqrt{n}}$$

$$n(\vec{r}) \propto \exp\left(-\frac{V^*(\vec{r})}{k_B T}\right)$$

$$V^*(r) = V(r) + \frac{\hbar^2}{4m_{x,y} r k_B T}\left[\nabla^2 V^*(r) - \frac{1}{2}\frac{1}{k_B T}\left(\nabla V^*(r)\right)^2\right] \cdots (1)$$

$$\frac{dk}{dt} = -\frac{1}{\hbar}\nabla_r V^*(r) \cdots (2)$$

V(r): Potential
V*(r): Quantum Corrected Potential
E(r): Electric Field

Fig.2. Bohm potential quantum correction method. Bohm potential is calculated by potential and it converts to electric field.

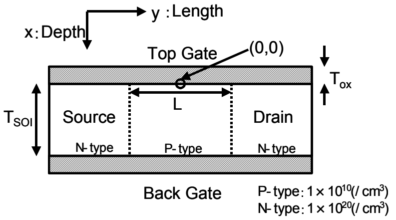


Fig.3. Simulated DG structure. The channel region is assumed to be intrinsic

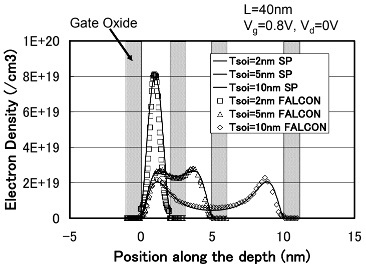


Fig.4. Comparison between Schrödinger – Poisson and Bohm potential method for different SOI thickness.

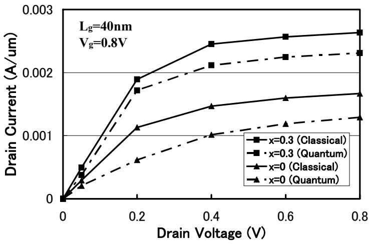


Fig.5. I_d-V_d characteristics for strain and quantum model.

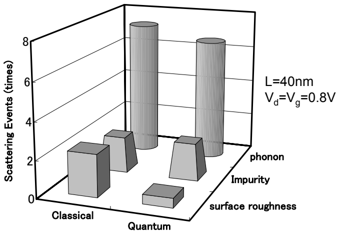


Fig.6. Scattering mechanism for classical and quantum transports.

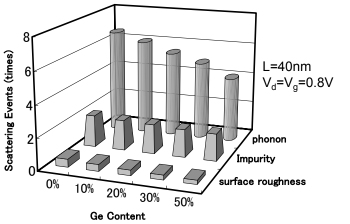


Fig.7. Scattering mechanism analysis for different Ge content.

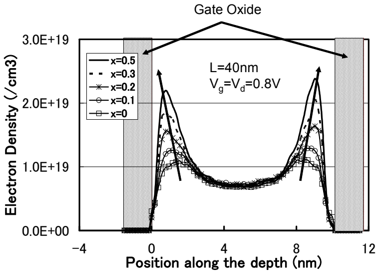


Fig.8. Electron distribution for different Ge content. Increasing Ge content, carrier peak shifts to the oxide-silicon surface.

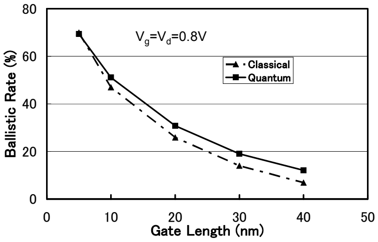


Fig.9. Ballistic rate of classical and quantum model with scaling

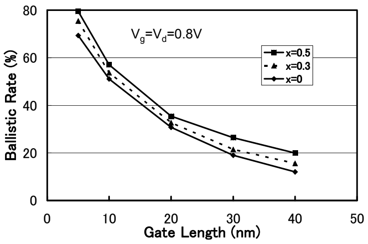


Fig.10. Ballistic rate in quantum model with scaling for different Ge content

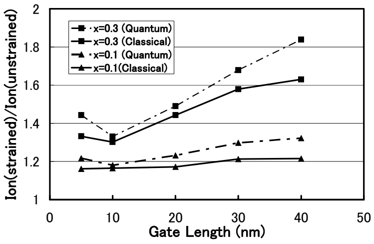


Fig.11. Ion improvement ratio for scaling.

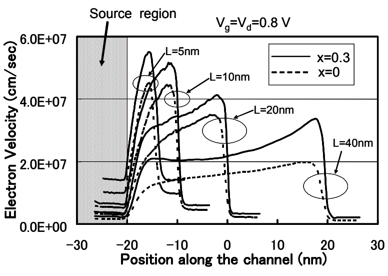


Fig.12. Electron velocity in quantum model for each gate length.

A full journal publication of this work will be published in the Journal of Computational Electronics.