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Experimental Study on Hall Factor in Ultrathin-Body SOI n-MOSFETs

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Introduction

For immunity to the short channel effects, ultrathin-body (UTB) SOI FETs have been attracted much attention. Thanks to intensive studies, unique carrier scatterings due to the strong carrier confinements in the UTB structures are relatively well understood[1-4]. A large portion of the understanding on the carrier scatterings, however, was acquired through the mobility (μ) characterizations, in spite of the fact that μ provides with only scattering rates ($1/\tau$, τ is the scattering relaxation time) averaged over the carrier energy (ε). Thus, to promote the understanding of the carrier scatterings, other physical quantities should be measured experimentally, and the scattering models should be refined from new aspects of the carrier scatterings.

In this study, we investigate experimentally Hall factor (γ_H) in UTB SOI nFETs. The first systematic data on γ_H is useful to refine the carrier scattering models, since γ_H reflects an inherent characteristics of the carrier scatterings which is not obtainable by the μ characterizations: dependence of $1/\tau$ on ε.

Device Structures and Extraction of γ_H

Long-channel nFETs (L/W=200/100μm) fabricated on (001) SOI wafers were used. The channel direction was <110>. As show in Fig.1, SOI thickness (T_{SOI}) in the channel region was selectively thinned down to sub-10nm, whereas T_{SOI} of source and drain were more than 60nm to eliminate the effects of the parasitic resistance[4].T_{SOI} was evaluated by using the correlation between T_{SOI} and the threshold voltage shift induced by the back gate bias[4]. The gate dielectric and the gate electrode were 20nm-thick SiO_2 and poly-Si, respectively. The devices had additional terminals for the Hall voltage (V_H) measurements, as shown in Fig.2.

Fig.2 shows the procedure for extraction of γ_H. Firstly, V_H was measured by Hall effect measurements. The magnetic field of 0.3T was applied perpendicularly to the wafer surface, and 50mV was biased to drain. Next, surface carrier concentrations (N_s) were measured by the split-CV method. Then, γ_H^{Exp} was obtained by using the eq. in Fig.2[5-7]. To obtain γ_H, the two corrections were made on γ_H^{Exp} in terms of (1) the unisotropy of the effective mass (m^*) in the fourfold valleys and (2) the Hall bar geometry[5-7]. The correction factor for m^* unisotropy (α_{m^*}) was calculated considering the occupation probability of the fourfold valleys for each N_s. The occupation probability was calculated by solving Poisson and Schrodinger eqs. selfconsistently. The correction factor for the Hall bar geometry (α_G) was determined following to ref.7. γ_H was extracted by multiplying γ_H^{Exp} by α_{m^*} and α_G.

Fig.3 shows schematic relationships between $1/\tau$ and ε. In general, $1/\tau$ of Phonon scattering increases when carriers gain higher ε. γ_H reflects the differential of $1/\tau$, and larger γ_H indicates that $1/\tau$ increases more rapidly with an increase of ε.

Experimental Results

At first, μ was measured to check the device qualities. Fig.4 shows μ of various T_{SOI} devices as a function of N_s. Universal μ is also shown for comparison[8]. Fig.5 shows μ at N_s of 5e12cm^{-2} as a function of T_{SOI}. As reported by many authors[1-4], μ increases as T_{SOI} decreases from 4.5nm to 3.3nm. This μ enhancement suggests that the SOI thinning was successful so that the energy leveles of subbands were controlled well by T_{SOI}, since subband calculations predicted that μ is enhanced in T_{SOI} of about 3.5nm[1-4].

Fig.6 shows γ_H of the three devices with T_{SOI} of 8.2nm, 4.0nm, and 2.5nm as a function of N_s. In the whole measured range of N_s, γ_H decreases as T_{SOI} becomes thinner. Note that γ_H of the 2.5nm-thick-T_{SOI} device is almost unity, indicating that ε dependence of $1/\tau$ is negligibly weak. Fig.7 shows γ_H at N_s of 5e12cm^{-2} as a function of T_{SOI}. When T_{SOI} is thicker than 4.2nm, γ_H is about 1.15 and decreases slightly in thinner T_{SOI}. On the other hand, when T_{SOI} is thinner than 4.2nm, γ_H decreases drastically, and γ_H becomes almost unity in T_{SOI} of 2.5nm.

Discussions

To clarify the factor which determines γ_H, measured γ_H is compared with calculated γ_H. γ_H was calculated by using the expression of $\gamma_H=\langle\tau^2\rangle/\langle\tau\rangle^2$, where $\langle\tau\rangle$ is the average of τ considering ε dependence[5,6]. In calculations, only Phonon scattering was considered. We used the conventional Phonon scattering model with the parameters listed in Table 1[9,10]. Fig.8 shows γ_H calculated for the three T_{SOI} of 8.2nm, 4.0nm, and 2.5nm. Although calculated γ_H is smaller than measured γ_H, the calculations reproduce well the overall properties of measured γ_H; γ_H of the 8.2nm-thick T_{SOI} device decreases at higher N_s, and that of the 2.5nm-thick T_{SOI} device is almost unity in the whole calculated range of N_s. Fig.9 shows calculated γ_H at N_s of 5e12cm^{-2} as a function of T_{SOI}. The solid circle denotes γ_H calculated considering both the intravalley and intervalley scatterings, whereas open circle and square denote γ_H calculated considering only the intravalley or intervalley scatterings, respectively. Except the calculated peak of γ_H in T_{SOI} of 4.0nm, the calculations reproduce well the slight γ_H reduction in T_{SOI} of thicker than 4.2nm and the drastic γ_H reduction in T_{SOI} of thinner than 4.2nm. From Fig.9, it is also clear that γ_H is determined mainly by the intravalley scatterings.

Next, the physical reason why the intravalley scatterings determine dominantly γ_H is considered. In Phonon scattering, $1/\tau$ of the intrasubband scatterings do not depend on ε, indicating that γ_H is unity if only the intravalley scatterings occur. In contrast, since scatterings to the higher energy subbands occur only if electrons have sufficiently large ε, $1/\tau$ of the intersubband scatterings depends on ε. When the intersubband scatterings increases, the ε dependence of $1/\tau$ is enhanced, resulting in higher γ_H. As shown in Fig.10, most of the low energy subbands are formed by the twofold valleys in T_{SOI} ranged from 9.0nm to 2.0nm. Since the intersubband scatterings occur among the low energy subbands, most of the intersubband scatterings are the intravalley scatterings of the twofold valleys. Thus, γ_H is determined mainly by the intravalley scatterings. To confirm the scenario, γ_H was calculated considering only the intersubband and intravalley scatterings of the twofold and fourfold valleys (Fig.11). For the intersubband scatterings, scatterings to the higher energy subbands were only counted. It is clear that in the calculated range of T_{SOI}, the intravalley scatterings of the twofold valleys determined γ_H compared with that of the fourfold valleys, suggesting the validity of the scenario.

Conclusions

γ_H was investigated experimentally in UTB SOI nFETs for various T_{SOI}. It was found for the first time that when T_{SOI} is thicker than 4.2nm, γ_H decreases slightly in thinner T_{SOI}, whereas when T_{SOI} is thinner than 4.2nm, γ_H decreases drastically and becomes almost unity in T_{SOI} of 2.5nm. By comparing with calculations, it was also found that γ_H is determined mainly by the intravalley scatterings, particularly that of the twofold valleys. The dominance of the intravalley scatterings in the γ_H determination is attributed to the energy levels of subbands by which most of the ε-dependent-scatterings are the intravalley scatterings of the twofold valleys.

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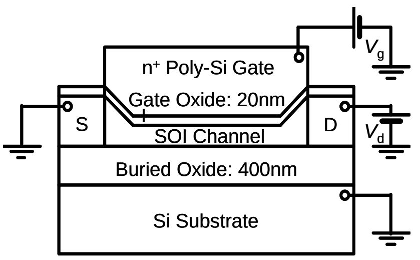

Fig.1 Schematic of ultrathin-body (UTB) nFET on the SOI wafer, and the bias conditions for Hall effect measurements. For the back gate bias, Si substrate beneath the buried oxide was used as the back gate.

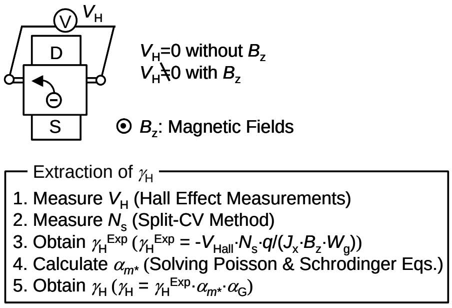

Fig.2 Schematic of Hall effect measurements, and the procedure for extraction of Hall factor (γ_H).

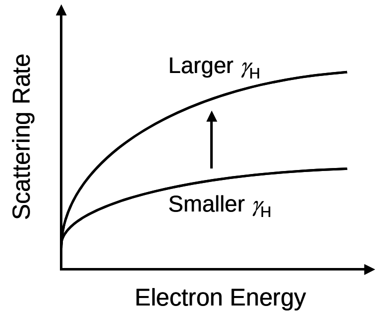

Fig.3 Schematic relationships between scattering rate ($1/\tau$) and electron energy (ε) with different γ_H.

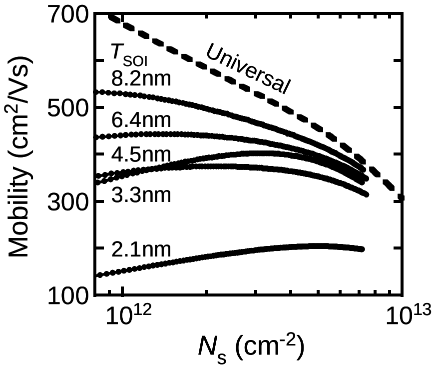

Fig.4 Mobility (μ) of the devices having various T_{SOI} as a function of the surface carrier concentration (N_s).

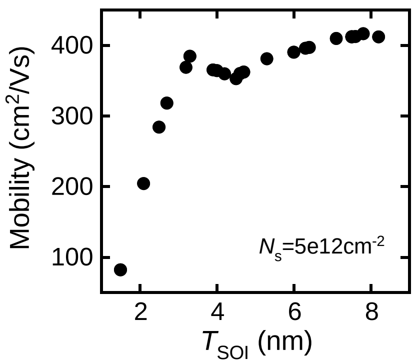

Fig.5 μ at N_s of 5e12cm^{-2} as a function of T_{SOI}. μ peak is observed in T_{SOI} of 3.3nm.

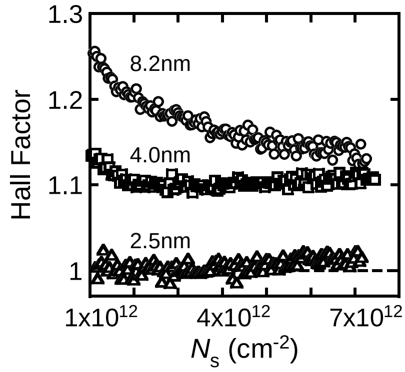

Fig.6 Hall factor (γ_H) of the three devices with different T_{SOI} as a function of N_s.

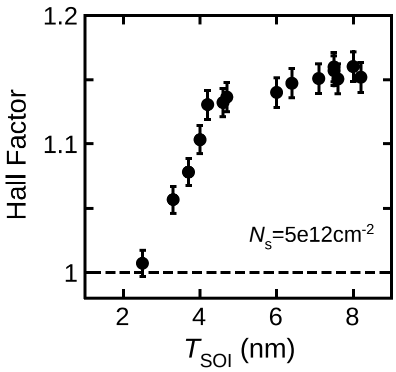

Fig.7 γ_H at N_s of 5e12cm^{-2} as a function of T_{SOI}.

Table 1 Parameters used to calculate $1/\tau$ of Phonon scattering.

Intravalley Scattering		
Crystal Density	2329kg/m^2	
Sound Velocity	9037m/s	
D_{ac}	12.5eV	
Intervalley Scattering		
Scattering Type	E_k (meV)	D_k (10^8eV/cm)
f	19.0	0.3
f	47.5	2.0
f	59.1	2.0
g	12.1	0.5
g	18.6	0.8
g	62.2	11.0

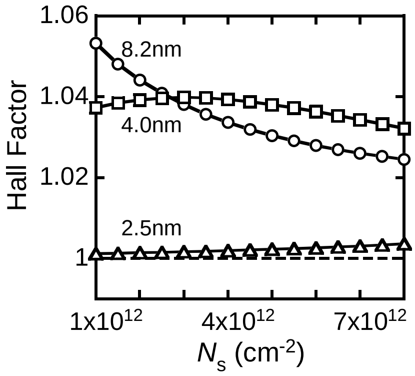

Fig.8 Calculated γ_H for the three different T_{SOI} as a function of N_s.

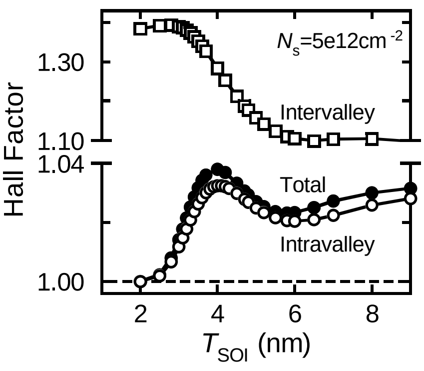

Fig.9 Calculated γ_H at N_s of 5e12cm^{-2} as a function of T_{SOI}. The solid circle denotes γ_H calculated considering both the intravalley and intervalley scatterings, whereas open circle and square denote γ_H calculated considering only intravalley or intervalley scatterings, respectively.

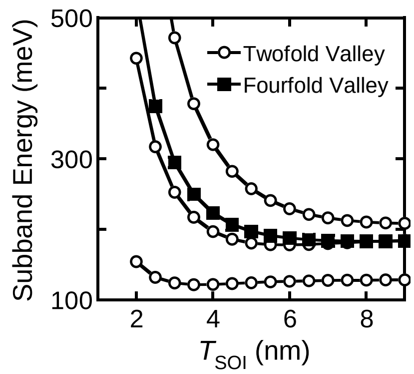

Fig.10 Energy levels of the four lowest subbands as a function of T_{SOI}. Energy origin is set to the conduction band edge at the interface between the front oxide and the SOI layer. Open circle denotes the subband formed by the twofold valley, whereas solid square denotes the subband formed by the fourfold valley.

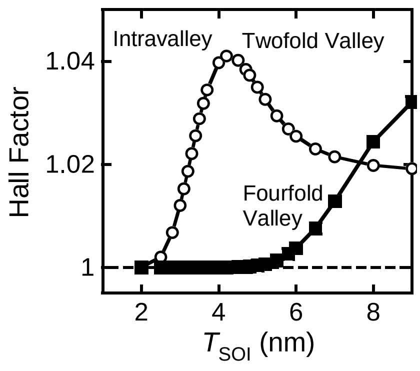

Fig.11, γ_H calculated considering only the intersubband and intravalley scatterings of the twofold (open circle) and fourfold valleys (solid square) as a function of T_{SOI}. For the intersubband scatterings, scatterings to the higher energy subbands were only counted.