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Influence of fixed charges and trapped electrons on free electron mobility at 4H-SiC(0001)/SiO₂ interfaces with gate oxides annealed in NO or POCl₃

Koji Ito^{1*}, Hajime Tanaka^{1,2}, Masahiro Horita³, Jun Suda³, and Tsunenobu Kimoto¹

¹Department of Electronic Science and Engineering, Kyoto University, Nishikyō, Kyoto 615-8510, Japan

²Division of Electrical, Electronic and Infocommunications Engineering, Osaka University, Suita, Osaka 565-0871, Japan

³Department of Electrical Engineering, Electronics, and Information Engineering, Nagoya University, Higashi-cho, Chikusa, Nagoya, Aichi 464-8603, Japan

*E-mail: ito@semicon.kuee.kyoto-u.ac.jp

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Free electron mobility (μ_{free}) in 4H-SiC(0001) MOSFETs with gate oxides annealed in NO or POCl₃ was calculated in a wide range of effective normal field (E_{eff}) from 0.02 to 2 MV cm⁻¹, taking account of scattering by fixed charges and trapped electrons. The present calculation indicates that the Hall mobility in the high- E_{eff} region experimentally obtained for NO-annealed MOSFETs (14 cm² V⁻¹ s⁻¹ at 1.1 MV cm⁻¹) is much lower than that for POCl₃-annealed MOSFETs (41 cm² V⁻¹ s⁻¹) due to severe Coulomb scattering by electrons trapped at a very high density of interface states. © 2024 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

4H-SiC has superior physical properties for power device applications such as a wide bandgap and high critical electric field. In particular, SiC MOSFETs have been regarded as next-generation high-voltage and low-loss power switches.^{1,2)} To predict the characteristics of SiC MOSFETs, modeling of free electron mobility (μ_{free}) at the interface between SiC and SiO₂ is one of the most important issues to be clarified. However, μ_{free} at the SiC/SiO₂ interface is not fully understood at the present stage.

Extraction of μ_{free} from characteristics of SiC MOSFETs is very difficult because the interface state density at the SiC/SiO₂ interface is much higher ($\sim 10^{13}$ cm⁻² eV⁻¹) than that at Si/SiO₂.³⁻⁹⁾ The interface states at SiC/SiO₂ capture electrons in the inversion layers of the n-channel MOSFETs and decrease the effective mobility (μ_{eff}) obtained from the MOSFET characteristics,¹⁰⁾ leading to considerably lower μ_{eff} than μ_{free} . For this reason, MOS-Hall effect measurements were performed, and Hall electron mobility (μ_{Hall}) was discussed in previous reports.^{8,10-15)} References 14 and 15 investigated the influence of Coulomb scattering on μ_{Hall} . Reference 14 reported that trapped electrons may not serve as strong Coulomb scattering centers, given the minimal difference in μ_{Hall} between as-oxidized and NO-annealed MOSFETs. Reference 15 proposed that trapped electrons were not considered as Coulomb scattering centers and modeled μ_{Hall} through Coulomb scattering exclusively by fixed charges. Consequently, previous studies have not focused on Coulomb scattering due to both fixed charges and trapped electrons. We recently reported that the μ_{Hall} of MOSFETs annealed in POCl₃ under the high effective normal field was about three times higher than that of MOSFETs annealed in NO and suggested that this higher μ_{Hall} may originate from the lower trapped electron density (n_{trap}).¹⁶⁾ In our previous study, however, the influence of n_{trap} on μ_{Hall} was not quantitatively discussed. Theoretical studies on the scattering mechanism using numerical calculations have also been conducted.^{17,18)} In the present study, we theoretically calculate the μ_{free} of MOSFETs annealed in POCl₃ or NO including scattering due to the trapped

electrons, and compare it with the μ_{Hall} experimentally obtained based on the scattering rates in Ref. 17. The neutral defect scattering¹⁷⁾ and dipole scattering¹⁸⁾ were not considered in the present calculation to make the model simple.

MOSFETs annealed in POCl₃ or NO were fabricated on 4H-SiC(0001) epitaxial substrates with the acceptor concentrations (N_A) of 3×10^{14} and 1×10^{15} cm⁻³. The other p-body doping concentrations of 3×10^{16} – 3×10^{18} cm⁻³ were formed by Al ion implantation. The gate oxides annealed in POCl₃¹⁹⁾ or NO²⁰⁾ were formed by dry oxidation at 1300 °C for 30 min followed either by annealing in a gas mixture of POCl₃, O₂, and N₂ at 1000 °C for 10 min with subsequent annealing in N₂ at 1000 °C for 30 min, or by annealing in NO (10% diluted in N₂) at 1250 °C for 70 min, respectively. The gate oxide thicknesses annealed in POCl₃ and NO were 58 nm and 42 nm, respectively. The device structure and measurement condition of the MOS-Hall effect were explained in our previous report.¹⁶⁾ In this study, the Hall scattering factor was assumed to be unity, and thus μ_{Hall} was assumed to be equal to μ_{free} . Under this assumption, the Hall electron density experimentally obtained was regarded as the free electron density (n_{free}).

In the calculation, we firstly considered the following scattering processes: acoustic phonon scattering, non-polar optical phonon scattering, and Coulomb scattering due to the substrate impurities because the influence of these scattering processes can be calculated by choosing the physical parameters already reported by previous studies, such as the deformation potential of bulk 4H-SiC. The energy (E)–wave vector (k_x , k_y) dispersion was determined by assuming the effective mass approximation and by considering the three lowest and three second lowest conduction band valleys in 4H-SiC.²¹⁾ The conduction band edge of the second lowest valley is higher than that of the lowest valley by 0.12 eV.²¹⁾ The effective masses (m_{MT} , m_{MK} , and m_{ML}) used in the calculation of the present study were taken from the density functional theory (DFT) results using the PW potential in Table IV in Ref. 21. The x and y directions are parallel to the MOS interface while the z direction is perpendicular to it. The wave function (ξ_n) and energy (E_n) of the n th sub-band



were obtained by self-consistently solving Schrödinger and Poisson equations.^{22,23)} The μ_{free} was calculated under the relaxation time approximation by

$$\mu_{\text{free}} = \sum_{m=0}^{\infty} \frac{n_m}{n_{\text{free}}} \frac{e \langle \tau_m \rangle}{m_c}, \quad (1)$$

$$\langle \tau_m \rangle = \frac{\int_{E_m}^{\infty} \tau_m(E - E_m) F_{\text{FD}}(E) [1 - F_{\text{FD}}(E)] dE}{\int_{E_m}^{\infty} (E - E_m) F_{\text{FD}}(E) [1 - F_{\text{FD}}(E)] dE}, \quad (2)$$

$$\frac{1}{\tau_m(E)} = \sum_i \frac{1}{\tau_m^i(E)}, \quad (3)$$

where n_m is the electron density in the m th sub-band, $\langle \tau_m \rangle$ is the average momentum relaxation time of the m th sub-band, $m_c = 2/(1/m_{\text{MT}} + 1/m_{\text{MK}})$ is the conductivity effective mass, τ_m is the momentum relaxation time of the m th sub-band, $F_{\text{FD}}(E) = [1 + \exp((E - E_{\text{F}})/k_{\text{B}}T)]^{-1}$ is the Fermi–Dirac distribution function, and i in τ_m^i denotes the type of scattering.

The τ_m determined by acoustic phonons (τ_m^{ac}) is given by^(24,25)

$$\frac{1}{\tau_m^{\text{ac}}(E)} = \sum_{n=0}^{\infty} \frac{m_d D_{\text{ac}}^2 k_B T}{\hbar^3 \rho_{\text{SiC}} v_{\text{SiC}}^2} \int_0^{\infty} |\xi_n(z)|^2 |\xi_m(z)|^2 dz \times u(E - E_n), \quad (4)$$

where m_d is the density-of-states effective mass, D_{ac} is the deformation potential for acoustic phonons (D_{ac} is assumed to be $11.6 \text{ eV} \times 12/9 = 15.5 \text{ eV}$),^{17,26)} k_B is the Boltzmann constant, $\hbar$ is the Dirac constant, ρ_{SiC} is the mass density of SiC ($\rho_{\text{SiC}} = 3211 \text{ kg m}^{-3}$),¹⁷⁾ v_{SiC} is the sound velocity of SiC ($v_{\text{SiC}} = 13730 \text{ m s}^{-1}$),¹⁷⁾ $u(x)$ is the step function [$u(x) = 1$ for $x \geq 0$ and $u(x) = 0$ for $x < 0$].

The τ_m determined by optical phonons (τ_m^{nop}) is calculated by the summation of the τ_m^{nop} for phonon absorption ($\tau_m^{\text{nop,ab}}$) and emission ($\tau_m^{\text{nop,em}}$) processes. The $\tau_m^{\text{nop,em}}$ is given by^{24,25)}

$$\frac{1}{\tau_m^{\text{nop,em}}(E)} = \sum_{n=0}^{\infty} \frac{Z_{\text{nop}} D_{\text{nop}}^2 m_d}{2\rho_{\text{SiC}} \hbar^2 \omega_{\text{nop}}} N \left(\hbar \omega_{\text{nop}} + \frac{1}{2} \mp \frac{1}{2} \right) \times \int_0^{\infty} |\xi_n(z)|^2 |\xi_m(z)|^2 dz \times u(E - E_n \pm \hbar \omega_{\text{nop}}) \times \frac{1 - F_{\text{FD}}(E \pm \hbar \omega_{\text{nop}})}{1 - F_{\text{FD}}(E)}, \quad (5)$$

where $Z_{\text{nop}} [=3 \text{ (intra-valley: 1, inter-valley: 2)}]$ ¹⁷⁾ is the number of equivalent conduction band valleys for each energy of conduction band (E_C or $E_C + 0.12 \text{ eV}$) to which electrons transition as a result of intra- and inter-valley optical phonon scattering, D_{nop} is the deformation potential of optical phonons and is considered to be $2.3 \times 10^9 \times \sqrt{4/3} \text{ eV cm}^{-1}$ because the previous study assumed that the number of final states in the conduction band valleys was four,²⁶⁾ $\hbar\omega_{\text{nop}}$ is the energy of optical phonons ($\hbar\omega_{\text{nop}} = 85 \text{ meV}$),²⁶⁾ and $N(E) = [\exp(E/k_B T) - 1]^{-1}$ is the Bose-Einstein distribution function. In the present study, the transition of electrons neither from the lowest conduction band (E_C) to the second lowest one ($E_C + 0.12 \text{ eV}$) nor from the second lowest one to the lowest one was not considered.

The τ_m determined by substrate impurities (τ_m^{imp}) is given by^{24,25)}

$$\begin{aligned} \frac{1}{\tau_m^{\text{imp}}(E)} &= \sum_{n=0}^{\infty} \frac{m_d e^4}{8\pi \hbar^3 (\kappa_{\text{SiC}} \varepsilon_0)^2} \\ &\times \int_0^{2\pi} \frac{\int_0^{\infty} |I_{mn}(q, z_0)|^2 g_{\text{imp}}(z_0) dz_0 (1 - \cos \theta)}{q(\theta)^2 \varepsilon(q)^2} d\theta \\ &\times u\left(k^2 - \frac{2m_c}{\hbar^2} (E_n - E_m)\right), \end{aligned} \quad (6)$$

where e is the elementary charge, κ_{SiC} is the relative permittivity of SiC, ε_0 is the permittivity of vacuum, q is the wave vector difference between the initial and final states, θ is the scattering angle, g_{imp} is the volume density of substrate impurities, $\varepsilon(q)$ is the dielectric function, and $k = (k_x^2 + k_y^2)^{1/2}$ is the wave number. In addition, I_{mn} is expressed by^{24,25)}

$$I_{mn}(q, z_0) = \int_0^\infty \xi_n^*(z) \xi_m(z) \left[e^{-q|z-z_0|} + \frac{\kappa_{\text{SiC}} - \kappa_{\text{SiO}_2}}{\kappa_{\text{SiC}} + \kappa_{\text{SiO}_2}} e^{-q(z+z_0)} \right] dz, \quad (7)$$

where κ_{SiO_2} is the relative permittivity of SiO_2 and z_0 is the position of a point charge which produces Coulomb potential. The $\varepsilon(q)$ in Eq. (6) is given by²⁵⁾

$$\varepsilon(q) = 1 - \sum_{l=0}^{\infty} \frac{e^2}{2q(\theta)\kappa_{\text{SiC}}\varepsilon_0} P_l(q) H_{00}(q), \quad (8)$$

$$P_l(q) = \frac{2n_v m_d}{(2\pi)^2 \hbar^2} \int_0^{2\pi} \int_0^\infty \frac{F_{\text{FD}}(E_l(\mathbf{k} + \mathbf{q})) - F_{\text{FD}}(E_l(\mathbf{k}))}{E_l(\mathbf{k} + \mathbf{q}) - E_l(\mathbf{k})} dE_p d\theta, \quad (9)$$

$$H_{00}(q) = \int_0^\infty \int_0^\infty |\xi_0(z_1)|^2 |\xi_0(z_2)|^2 \times \left[e^{-q|z_1 - z_2|} + \frac{\kappa_{\text{SiC}}}{\kappa_{\text{SiC}} + \kappa_{\text{SiO}_2}} e^{-q(z_1 + |z_2|)} \right] dz_1 dz_2, \quad (10)$$

where $n_v (=3)$ is the number of equivalent valleys and E_l is the energy of the l th sub-band.

Figure 1 shows the experimental μ_{Hall} , which is reused from Ref. 16, and calculated μ_{free} limited by phonon scattering and Coulomb scattering due to the substrate

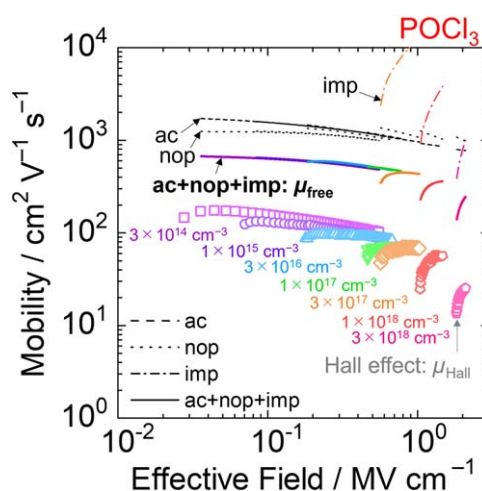


Fig. 1. Effective normal field dependence of experimental Hall mobility (μ_{Hall})¹⁶⁾ and calculated free electron mobility (μ_{free}) for SiC(0001) MOSFETs annealed in POCl₃ with various p-body doping concentrations ($3 \times 10^{14} \text{ cm}^{-3} \leq N_A \leq 3 \times 10^{18} \text{ cm}^{-3}$). The experimental Hall mobilities are represented by symbols. The calculated mobilities limited by acoustic phonons (ac), optical phonons (nop), substrate impurities (imp), and all of those scattering sources (ac+nop+imp: μ_{free}) are shown by dashed, dotted, dashed-dotted, and solid lines, respectively.

impurities for MOSFETs annealed in POCl_3 with various N_A of p-body as a function of the effective normal field (E_{eff}). The E_{eff} is written as²⁷⁾

$$E_{\text{eff}}(n_{\text{free}}) = \frac{\sqrt{2e\kappa_{\text{SiC}}\varepsilon_0 N_A(2\psi_B) + \eta n_{\text{free}}}}{\kappa_{\text{SiC}}\varepsilon_0}, \quad (11)$$

where ψ_B is the bulk potential, η is the parameter that indicates how much the electrons contribute to the normal field. In the present study, η is assumed to be 1/3.^{13,28,29)} As can be seen, the calculated μ_{free} is about 4 times higher than the experimental μ_{Hall} , which is consistent with the previous studies.^{17,18)} The calculated μ_{free} (“ac+nop+imp” in Fig. 1) represents the upper limit of μ_{free} in SiC MOSFETs with an ideal MOS interface (no interface charges).

Based on the above discussion, we additionally took account of Coulomb scattering due to fixed charges and surface roughness scattering. The momentum relaxation time of electrons in the m th sub-band determined by fixed charges (τ_m^{fix}) is expressed by substituting $N_{\text{fix}}\delta(z-z_{\text{it}})$ for $g_{\text{imp}}(z)$ in Eq. (6) as

$$\frac{1}{\tau_m^{\text{fix}}(E)} = \sum_{n=0}^{\infty} \frac{m_d e^4}{8\pi\hbar^3(\kappa_{\text{SiC}}\varepsilon_0)^2} \int_0^{2\pi} \frac{|U_{mn}(q, z_{\text{it}})|^2 N_{\text{fix}}(1 - \cos\theta)}{q(\theta)^2 \varepsilon(q)^2} d\theta \times u\left(k^2 - \frac{2m_c}{\hbar^2}(E_n - E_m)\right), \quad (12)$$

where z_{it} is just at the interface between SiC and SiO_2 , which is the position of the fixed charges, and N_{fix} is the area density of the fixed charges. In the present study, the N_{fix} was defined as the sum of the densities of positive and negative charges at the SiC/ SiO_2 interface. Therefore, N_{fix} is not equal to the effective charge density extracted from the threshold voltage shift because it represents the net fixed charge density. The positive and negative charge densities are constant and do not depend on the gate voltage.

The τ_m determined by surface roughness (τ_m^{sr}) is calculated by²⁵⁾

$$\frac{1}{\tau_m^{\text{sr}}(E)} = \sum_{n=0}^{\infty} \frac{m_d e^2 E_{\text{eff},mn}^2 \Delta_{\text{sr}}^2 L_{\text{sr}}^2}{2\hbar^3} \int_0^{2\pi} \frac{\left(1 + \frac{q(\theta)^2 L_{\text{sr}}^2}{2}\right)^{-\frac{3}{2}} (1 - \cos\theta)}{\varepsilon(q)^2} d\theta \times u\left(k^2 - \frac{2m_c}{\hbar^2}(E_n - E_m)\right), \quad (13)$$

where Δ_{sr} and L_{sr} are the height and correlation length of surface roughness, respectively. In the present study, the autocorrelation function is assumed to be an exponential one²⁵⁾ because the experimental mobility can be reproduced by using the exponential correlation function in the case of Si MOSFETs.²⁴⁾ The $eE_{\text{eff},mn}$ is expressed by²⁵⁾

$$eE_{\text{eff},mn} = \left| \frac{\hbar^2}{2m_{\text{ML}}} \frac{d\xi_n^*(0)}{dz} \frac{d\xi_m(0)}{dz} \right|. \quad (14)$$

Figure 2 shows the experimental μ_{Hall} and calculated μ_{free} limited by phonon scattering, surface roughness scattering, and Coulomb scattering due to the substrate impurities and fixed charges as a function of E_{eff} . The experimental μ_{Hall} of MOSFETs annealed in POCl_3 can be mostly reproduced by taking account of Coulomb scattering due to the fixed charges and surface roughness scattering as shown in Fig. 2(a). In the present study, the N_{fix} was assumed to be $5.0 \times 10^{12} \text{ cm}^{-2}$ and $2.5 \times 10^{12} \text{ cm}^{-2}$ for MOSFETs annealed in POCl_3 and NO, respectively, to reproduce the μ_{Hall} in the low- E_{eff} range ($E_{\text{eff}} < 0.1 \text{ MV cm}^{-1}$). The validity of the determined value of N_{fix} is provided in the last part. In addition, the Δ_{sr} and L_{sr} were determined as 1.0 nm and 5.0 nm, respectively, to reproduce the μ_{Hall} of MOSFETs annealed in POCl_3 in the high- E_{eff} range ($E_{\text{eff}} > 1.5 \text{ MV cm}^{-1}$). However, the μ_{Hall} drop in the high- E_{eff} region for MOSFETs annealed in NO cannot be reproduced by the scattering due to fixed charges and surface roughness only. For example, in the case of heavily-doped ($N_A = 3 \times 10^{17} \text{ cm}^{-3}$) MOSFETs annealed in POCl_3 , the experimental μ_{Hall} of $66 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is close to the

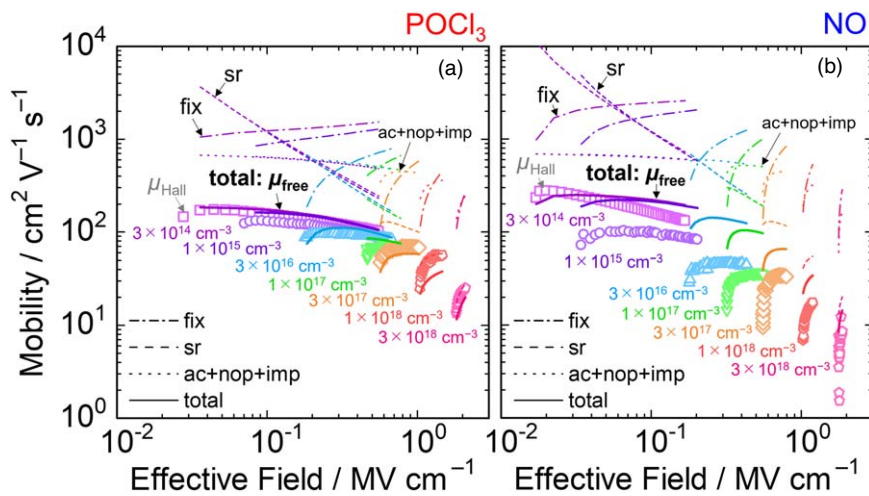


Fig. 2. Effective normal field (E_{eff}) dependences of experimental Hall mobility (μ_{Hall})¹⁶⁾ and calculated free electron mobility (μ_{free}) for SiC(0001) MOSFETs annealed in (a) POCl_3 and (b) NO. The experimental Hall mobilities are represented by symbols. The mobility denoted as ac+nop+imp in Fig. 1 is also shown by the dotted lines. The additionally calculated mobilities limited by fixed charges (fix), surface roughness (sr), and all of those scattering sources (total) are shown by dashed-dotted, dashed, and solid lines, respectively. The fixed charge density is determined as $5.0 \times 10^{12} \text{ cm}^{-2}$ and $2.5 \times 10^{12} \text{ cm}^{-2}$ for MOSFETs annealed in POCl_3 and NO, respectively. In addition, the height and correlation length of surface roughness are assumed to be 1.0 nm and 5.0 nm, respectively. A large difference between μ_{Hall} and μ_{free} (total) is observed in the high- E_{eff} region for NO-annealed MOSFETs.

calculated μ_{free} of $56 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at E_{eff} of 0.71 MV cm^{-1} . In contrast, for MOSFETs with the same N_A and annealed in NO, the experimental μ_{Hall} of $34 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is much smaller than the calculated μ_{free} of $65 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Therefore, we should additionally consider other scattering sources for MOSFETs annealed in NO.

In addition to the above calculation, we also took Coulomb scattering due to electrons trapped at the interface states into consideration. The τ_m determined by trapped electrons (τ_m^{trap}) is expressed by replacing N_{fix} in Eq. (12) with n_{trap} as

$$\frac{1}{\tau_m^{\text{trap}}(E)} = \sum_{n=0}^{\infty} \frac{m_d e^4}{8\pi \hbar^3 (\kappa_{\text{SiC}} \epsilon_0)^2} \int_0^{2\pi} \frac{|I_{mn}(q, z_{\text{it}})|^2 n_{\text{trap}} (1 - \cos \theta)}{q(\theta)^2 \epsilon(q)^2} d\theta \times u\left(k^2 - \frac{2m_c}{\hbar^2} (E_n - E_m)\right), \quad (15)$$

where the n_{trap} is the trapped electron density. In the present study, the n_{trap} was defined as the negative charges at interface states induced by an upward shift of the surface Fermi level. Thus, N_{fix} is constant and independent of the gate voltage, whereas the n_{trap} strongly depends on the gate voltage. In the present study, the n_{trap} as a function of n_{free} was taken from our experimental results of MOSFETs

annealed in POCl_3 or NO obtained by combining the MOS-Hall effect and split capacitance–voltage measurements as shown in Figs. 3(a) and 3(b).¹⁶⁾ The trapped electron density of NO-annealed MOSFETs is much higher than that of POCl_3 -annealed MOSFETs due to the considerably higher interface state density for NO-annealed MOS structures.

Figures 3(c) and 3(d) show the experimental μ_{Hall} and calculated μ_{free} limited by phonon scattering, surface roughness scattering, and Coulomb scattering due to the substrate impurities, fixed charges, and trapped electrons as a function of the E_{eff} . The same N_{fix} , Δ_{sr} , and L_{sr} as those in the calculation conditions of Fig. 2 were used. In the case of heavily-doped ($N_A = 3 \times 10^{17} \text{ cm}^{-3}$) MOSFETs annealed in POCl_3 shown in Fig. 3(c), the calculated μ_{free} of $55 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at E_{eff} of 0.71 MV cm^{-1} is very close to the μ_{free} of $56 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in Fig. 2(a). This result suggests that the impact of trapped electrons as Coulomb scattering centers is negligible in MOSFETs annealed in POCl_3 . On the other hand, for MOSFETs annealed in NO shown in Fig. 3(d), the calculated μ_{free} of $52 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is smaller than the calculated μ_{free} of $65 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in Fig. 2(b) at the same E_{eff} and N_A . As a result, the μ_{free} calculated considering Coulomb scattering due to trapped electrons becomes closer

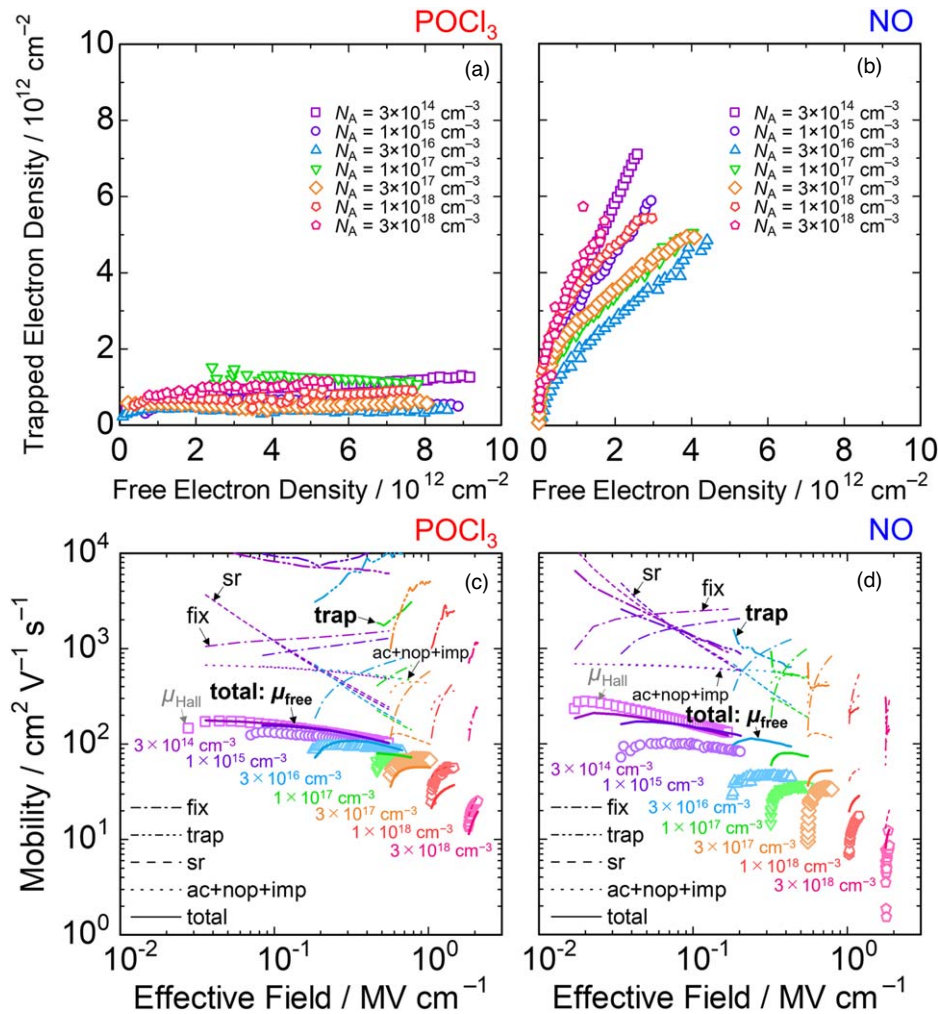


Fig. 3. Trapped electron density as a function of the free electron density taken from our previous experimental results of MOSFETs annealed in (a) POCl_3 or (b) NO¹⁶⁾ and effective normal field (E_{eff}) dependences of experimental Hall mobility (μ_{Hall})¹⁶⁾ and calculated free electron mobility (μ_{free}) for SiC(0001) MOSFETs annealed in (c) POCl_3 and (d) NO. The meanings of symbols and lines are the same as Fig. 2 but including scattering by trapped electrons (trap) shown by a dashed double-dotted line. The fixed charge density and the height and correlation length of surface roughness are also the same as those for Fig. 2. The difference between μ_{Hall} and μ_{free} (total) in the high- E_{eff} region for NO-annealed MOSFETs becomes smaller than that in Fig. 2.

to the experimental μ_{Hall} compared with the μ_{free} calculated without consideration of scattering by trapped electrons, especially for MOSFETs annealed in NO. Therefore, the significant difference in μ_{Hall} especially in the high- E_{eff} region between POCl₃-annealed and NO-annealed MOSFETs may be caused by Coulomb scattering due to the trapped electrons because the n_{trap} of $7.0 \times 10^{12} \text{ cm}^{-2}$ for MOSFETs annealed in NO is much larger than that of $8.9 \times 10^{11} \text{ cm}^{-2}$ for MOSFETs annealed in POCl₃ when the n_{free} is $2.5 \times 10^{12} \text{ cm}^{-2}$, as shown in Figs. 3(a) and 3(b).

Here, the validity of the determined value of N_{fix} is discussed. Figure 4 shows the μ_{free} of MOSFETs annealed in POCl₃ as a function of the E_{eff} calculated by changing the value of N_{fix} . The N_{fix} was assumed to be $1.0 \times 10^{12} \text{ cm}^{-2}$, $5.0 \times 10^{12} \text{ cm}^{-2}$, and $1.0 \times 10^{13} \text{ cm}^{-2}$ in Figs. 4(a)–4(c), respectively. In Fig. 4(b), the calculated μ_{free} is close to the experimental μ_{Hall} in the low- E_{eff} region ($E_{\text{eff}} < 0.1 \text{ MV cm}^{-1}$), where the scattering by the fixed charges is strong. For example, the experimental μ_{Hall} of $154 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is close to the μ_{free} of $159 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ calculated with $N_{\text{fix}} = 5.0 \times 10^{12} \text{ cm}^{-2}$ at E_{eff} of 0.11 MV cm^{-1} and N_{A} of $3 \times 10^{14} \text{ cm}^{-3}$. On the other hand, the μ_{free} of $120 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ calculated with $N_{\text{fix}} = 1.0 \times 10^{13} \text{ cm}^{-2}$ is 1.28 times lower than μ_{Hall} , suggesting that the higher N_{fix} of more than $1.0 \times 10^{13} \text{ cm}^{-2}$ is an unreasonable value. Here, the μ_{free} of $232 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ calculated with $N_{\text{fix}} = 1.0 \times 10^{12} \text{ cm}^{-2}$ is 1.51 times higher than μ_{Hall} . Although determining the exact lower limit of N_{fix} is difficult, it is obvious that Coulomb scattering due to fixed charges should be considered when comparing these calculated μ_{free} with the ideal μ_{free} indicated by “ac+nop+imp” in Fig. 1. The calculated μ_{free} strongly depends on the parameter N_{fix} as shown in Fig. 4, and an N_{fix} of $5.0 \times 10^{12} \text{ cm}^{-2}$ gives a reasonable agreement with the experimental data. In a similar way, N_{fix} for MOSFETs annealed in NO was determined to be $2.5 \times 10^{12} \text{ cm}^{-2}$. The N_{fix} was assumed to depend on the gate oxide formation process but remained constant regardless of the p-body doping concentration because the fixed charge density in Si MOSFETs is independent of the doping type and concentration.^{30,31} In our future study, it is necessary to investigate the doping concentration dependence of N_{fix} .

Next, the difference in μ_{free} between POCl₃-annealed and NO-annealed MOSFETs is discussed. A previous study reported that the μ_{Hall} at high temperature in MOSFETs annealed in POCl₃ is almost the same as that in MOSFETs annealed in NO,³² suggesting that the influence of phonon scattering in SiC MOSFETs is independent of whether the gate oxide is annealed by POCl₃ or NO. In addition, the scattering due to surface roughness in MOSFETs annealed in POCl₃ will be similar to that in MOSFETs annealed in NO from our atomic force microscope observation.³³ From the above discussion, we propose that the difference in μ_{Hall} between POCl₃-annealed and NO-annealed MOSFETs in the high- E_{eff} region can be explained mainly by scattering due to fixed charges and trapped electrons. This model does not contradict the previously reported model that the density of Coulomb scattering sources increases with increasing n_{free} in NO-annealed MOSFETs compared with POCl₃-annealed ones³² because the n_{trap} remarkably increases with increasing n_{free} in NO-annealed MOSFETs.^{8,16} In the other reports, Ref. 15 suggested that a very high fixed charge density of $4 \times 10^{13} \text{ cm}^{-2}$ severely limits the μ_{free} by comparing the Hall effect measurement results with the calculation results. Ref. 18 suggested that a high dipole density of $8 \times 10^{13} \text{ cm}^{-2}$ may strongly affect the μ_{free} . In both cases, they reported that the unidentified high density of Coulomb scattering centers decreases the μ_{free} . However, the reported fixed charge or dipole density seems to be unusually high. In contrast, the N_{fix} range of 2.5×10^{12} – $5.0 \times 10^{12} \text{ cm}^{-2}$ suggested in the present study is one-order-of-magnitude lower than the reported ones.^{15,18} This is attributed to the consideration of Coulomb scattering arising not only from the fixed charges but also from the trapped electrons.

In summary, μ_{free} of SiC MOSFETs annealed in POCl₃ or NO was theoretically calculated by considering Coulomb scattering due to fixed charges and trapped electrons and compared with the experimental μ_{Hall} . The μ_{Hall} was reproduced by setting N_{fix} as $5.0 \times 10^{12} \text{ cm}^{-2}$ and $2.5 \times 10^{12} \text{ cm}^{-2}$ for MOSFETs annealed in POCl₃ and NO, respectively. Furthermore, the calculation results indicated that the μ_{Hall} in the high- E_{eff} region of MOSFETs annealed in NO is lower than that of MOSFETs annealed in POCl₃ because the n_{trap} of MOSFETs annealed in NO is significantly higher than that of MOSFETs annealed in POCl₃.

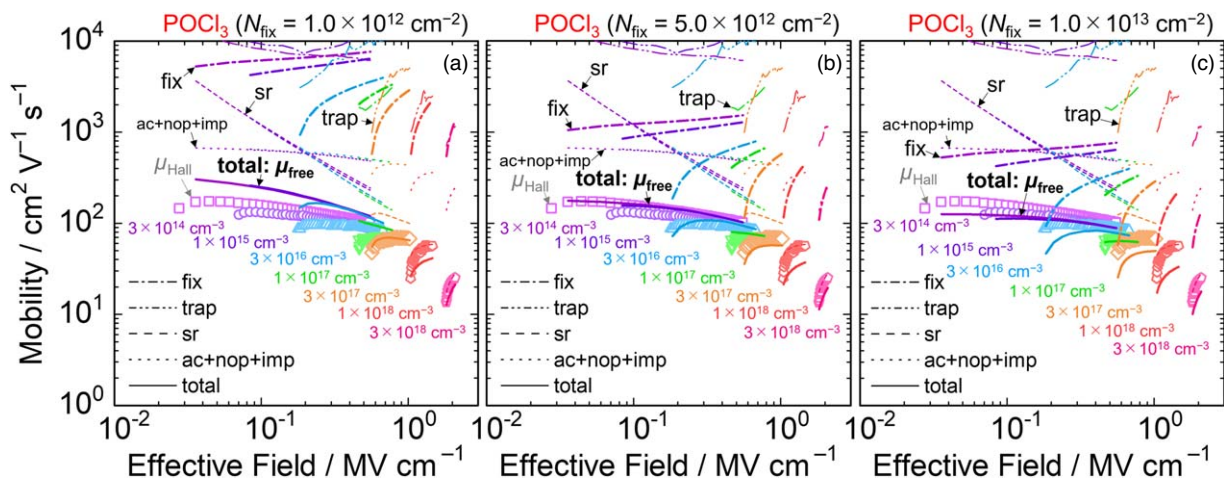


Fig. 4. Effective normal field dependences of experimental Hall mobility (μ_{Hall})¹⁶ and calculated free electron mobility (μ_{free}) for SiC(0001) MOSFETs annealed in POCl₃. The meanings of symbols and lines are the same as Figs. 3(c) and 3(d). The fixed charge density (N_{fix}) is set as (a) $1.0 \times 10^{12} \text{ cm}^{-2}$, (b) $5.0 \times 10^{12} \text{ cm}^{-2}$, and (c) $1.0 \times 10^{13} \text{ cm}^{-2}$. The height and correlation length of surface roughness are also the same as those for Fig. 2.

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ORCID iDs Koji Ito  <https://orcid.org/0000-0002-7229-2722> Hajime Tanaka  <https://orcid.org/0000-0001-9728-5687> Masahiro Horita  <https://orcid.org/0000-0003-0008-6732> Jun Suda  <https://orcid.org/0000-0002-5453-4943> Tsunenobu Kimoto  <https://orcid.org/0000-0002-6649-2090>

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