Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 12-13

A-1-4

Screening Effect on Remote Coulomb Scattering due to impurities in Polysilicon Gate of MOSFET

Takamitsu Ishihara, Junji Koga, Shinichi Takagi, and Kazuya Matsuzawa
Advanced LSI Thechnology Laboratory, Research and Development Center,Toshiba corporation
8 Shinsugita-cho, Isogo-ku, Yokohama 235-8522, Japan
Phone: +81-45-770-3691 Fax: +81-45-770-3578 e-mail:takamitsu.ishihara@toshiba.co.jp

1. Introduction

It has been reported that the inversion layer mobility exhibits a significant reduction in gate oxides thinner than a critical thickness[1]. Alhough several scattering mechanisms inherent to ultrathin gate oxides have been proposed, the reliable experimental results(Figure 1)[2,3] suggest that the mobility lowering in ultrathin gate oxides can be associated with remote Coulomb scattering(RCS) due to impurities in poly-Si-gate.

Mobility limited by RCS, μ_{rcs}, has been formulated so far by applying the depletion approximation(DA) to the poly-Si-gate. In the DA it is assumed that the depletion layer width, t_{depl}, in which no carriers exist is formed and the space charges within t_{depl} are responsible for RCS(Figure 2). However, it has been pointed out[4] that the screening effect on RCS by the carrier gas in poly-Si-gate is important for the quantitative evaluation of μ_{rcs}, since the high impurity concentration in the poly-Si-gate prevents the gate from being fully depleted. This fact is conformed from Figure 3, which shows the calculated results of the electron concentration in the n^+ poly-Si-gate as a parameter of surface electron concentration in the MOS channel. Fig. 3 clearly shows that non-negligible carriers exist in the poly-Si gate and thus DA does not hold.

In this study, RCS is formulated by taking into account the screening effect by the carrier gas in the poly-Si-gate under the co-existence of gate impurities. It is shown that the poly-Si-gate impurity concentration(N_{poly}) dependence of μ_{rcs} obtained experimentally is well represented by the present model, but not by the conventional DA model.

2. Model

As shown in Figure 4, the MOS structure is composed of a medium with permitivity ε_g for $z \le 0$(gate), an insulator with permittivity ε_{ox} for $0 < z \le t_{ox}$, and a silicon substrate with ε_{si} for $z \ge t_{ox}$. The impurity distribution in the poly-Si gate is expressed as $\rho_{ext}(\mathbf{r},z)$.

The key ideas in the present study are shown in Figure 5. The essential point is to formulate RCS as to include the screened Coulomb potential, which can not be taken into account in the DA. As shown in Fig. 4, the screening effect by the carrier gas in the poly-Si gate can be implemented through the induced charge density, $\rho_{ind}(\mathbf{r},z)$, around gate impurities, which is determined by solving the Poisson's equation for the poly-Si-gate(Fig. 4). The scattering potential for RCS can be evaluated by solving the Poisson's equation for both Si substrate and poly-Si-gate(Fig. 4). Thus, the screening effect by the carriers in poly-Si-gate can be automatically incorporated into RCS rate. The distribution of carriers in poly-Si-gate is evaluated by the device simulator.

3. Results

Figure 6 shows the comparison of the calculated results of μ_{rcs} by the present model with that by the DA. The most remarkable difference between these two models is that the N_{poly} dependence of μ_{rcs} is stronger in the present model than that in the DA, particularly in the low Ns region. This behavior is understood as follows.

In the DA, t_{depl} in the poly-Si-gate is determined from Eq. (1) in Fig. 2. Under the DA, t_{depl} becomes smaller with a decrease in Ns(according to Eq. (1)) and the RCS scattering rate becomes small. Therefore, μ_{rcs} shows almost no N_{poly} dependence because of the disappearance of scattering centers. In the high Ns region, the poly-Si-gate is fully depleted so that the N_{poly} dependence of μ_{rcs} is caused by the difference of t_{dep}.

On the other hand, the co-existence of charged impurities and free carriers in the gate region is taken into account under an appropriate consideration of the screening effect in the present model. The non-negligible screened Coulomb potential significantly reduces the inversion layer mobility and causes the stronger N_{poly} dependence of μ_{rcs}. In the high Ns region, in contrast, the poly-Si-gate is fully depleted so that the present model and the DA give the similar results.

Figure 7 shows the comparison of the experimental[2,3] and calculated results of μ_{rcs}. It is found that the N_{poly} dependence of μ_{rcs} is well represented by the present model, but not by the DA, meaning that the present model of RCS represents the mobility lowering in ultra-thin oxides better.

Figures 8 and 9 show the t_{ox} dependence of μ_{rcs}. Fig. 8 shows the remarkable degradation of μ_{rcs} with t_{ox} thinner than 1.5nm, supporting the experimental result[2,3]. It is also found from Fig. 9 that the t_{ox} dependence of μ_{rcs} is well reproduced by the present model.

4. Conclusions

Remote Coulomb scattering has been formulated by taking into account the co-existence of charged impurities and free carriers in the gate region under an appropriate consideration of the screening effect. The N_{poly} dependence of μ_{rcs} observed in the experiment can be well represented by the present model. This fact indicates the importance of the screening effect by the carrier gas in the poly-Si-gate on RCS and the responsibility of RCS on mobility lowering associated with ultra-thin gate oxides.

References

[1] G. Temp *et al.*, *Tech. Dig. Int. Electron Device Meet.*, p. 930, 1997.
[2] S. Takagi and M. Takayanagi, *Jpn. J. Appl. Phys.* ***41***, p.

2348, 2002.
[3] J. Koga et al., submitted to SSDM 2003.
[4] M. V. Fischetti, *J. Appl. Phys*. **89**, p. 1232, 2001.

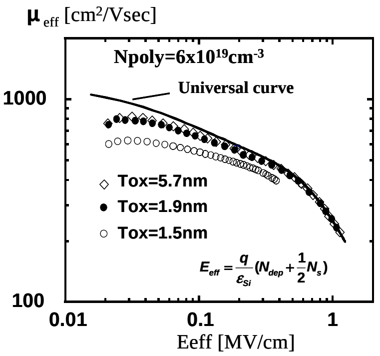

Fig. 1 Dependence of inversion-layer mobility on E_{eff} for nMOSFETs with different t_{ox}. The gate impurity concentration is 6×10^{19} cm^{-3}. Solid line stands for the universal mobility curve.

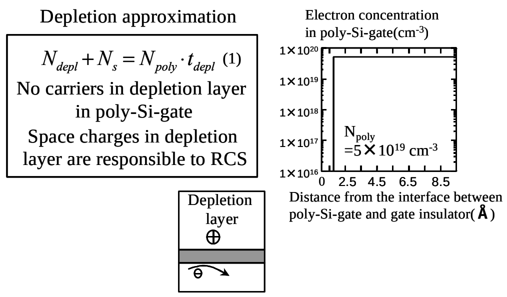

Fig. 2 Conceptual diagram which explains the key ideas of the depletion approximation. N_{depl}, Ns, t_{depl} are the depletion layer charge density in the substrate, surface carrier concentration, and the depletion layer width in the poly-Si-gate, respectively.

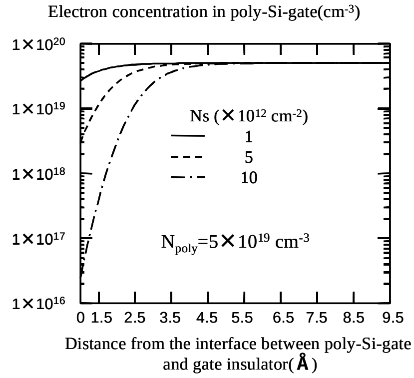

Fig. 3 Calculated results of the electron concentration in the n$^+$ poly-Si-gate as a parameter of surface electron concentration in MOS channel.

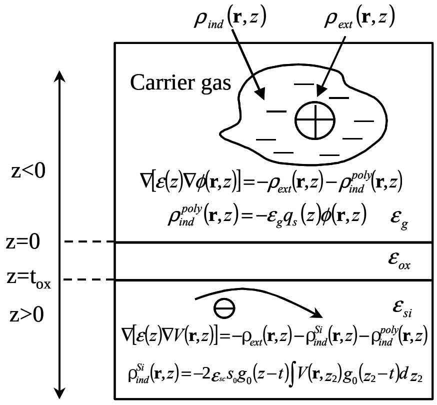

Fig. 4 Schematic diagram of the MOS structure. Poisson's equations solved in this study are also shown. q_s and s_0 are the screening parameter for poly-Si-gate and Si substrate, respectively. g_0 is the envelope function of lowest subband in the inversion layer.

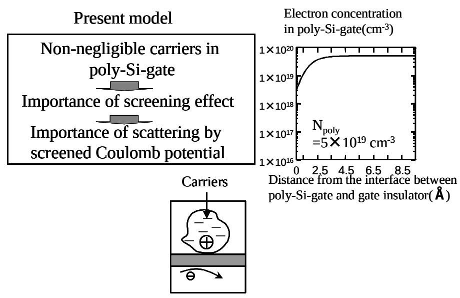

Fig. 5 Conceptual diagram which explains the key ideas of the present model.

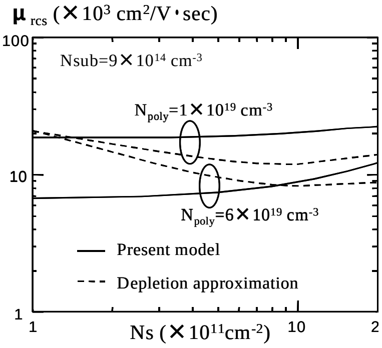

Fig. 6 Comparison of the calculated results of μ_{rcs} by the present model and depletion approximation.

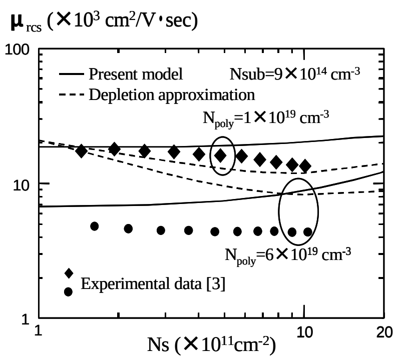

Fig. 7 Comparison of the experimental μ_{rcs} with that calculated by the present model and the depletion approximation.

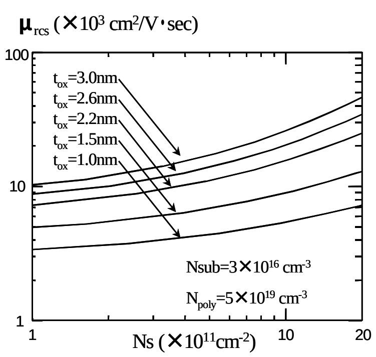

Fig. 8 Ns dependence of μ_{rcs} as a parameter of gate oxide thickness (t_{ox}).

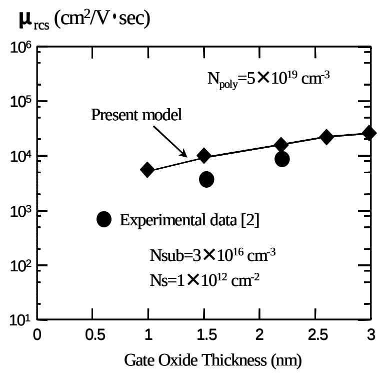

Fig. 9 Comparison of the experimental μ_{rcs} with that calculated by the present model as a function of t_{ox} at Ns of 1×10^{12} cm^{-2}.