Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 275-278

Effects of Surface Orientation on the Universality of Inversion-Layer Mobility in Si MOSFETs

Shin-ichi Takagi, Masao Iwase and Akira Toriumi
ULSI Research Center, TOSHIBA Corporation
1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan

Inversion-layer electron mobilities on (100), (110) and (111) surfaces have been studied from the viewpoint of universality. It has been found that the mobilities on (110) and (111) also have a universal relationship for effective field E_{eff} with $\eta=1/3$ instead of $\eta=1/2$. The E_{eff} dependences of the mobilities have been observed to be significantly different among the three surface orientations, which can be attributed to the differences in surface roughness scattering.

1. INTRODUCTION

The universal relationship between inversion-layer mobility and the effective normal field is known to be a useful concept in modeling the mobility in Si MOSFETs fabricated on a (100) surface[1-4]. However, the behavior of mobility on surface orientations different from (100) has not yet been fully understood, although it has already been reported that the surface orientation greatly affects mobility[5,6]. Since such non-planar MOSFETs as trench transistors and concave transistors can play an important role in future ULSIs, it is important to quantitatively evaluate the effects of the surface orientation on mobility. In this paper, the inversion-layer mobilities on (100), (110) and (111) surfaces have been characterized from the viewpoint of universality.

2. SAMPLE PREPARATION AND MEASUREMENTS

The measured devices were poly-Si gate N-channel MOSFETs on (100), (110) and (111) substrates. The substrate impurity concentration was varied using boron ion implantation, followed by long and high temperature annealing (1190 °C, 60 min.). The gate oxide was grown to a thickness of 25 nm in dry oxygen at 900 °C. The direction for the current flow was parallel to the <$\bar{1}$10> axis.

The inversion-layer mobility was determined from the drain conductance (V_d = 50 mV) and the gate-channel capacitance. The effective normal field E_{eff} was determined by the following equation.

$$E_{eff} = (q/\varepsilon_{Si})(N_{dpl} + \eta \cdot N_s) \qquad (1)$$

where N_{dpl} and N_s are the surface concentration of the depletion charge and inversion charge, respectively. Here, the value of η is a parameter which defines E_{eff}.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3-1 Dependence of E_{eff} on surface orientation

The mobility on (100) surface is known to follow a universal curve when plotted as a function of E_{eff} [1-4], although the origin of this universality has not been fully clarified yet. Here, it has been reported that the value of η is 1/2 for electrons and 1/3 for holes. Figures 1 and 2 show the E_{eff} dependences of electron mobilities on (110) and (111) at 300 K as a function of E_{eff} with η = 1/2 (Fig.(a)) and η = 1/3 (Fig.(b)). It has been found that the mobilities on (110) and (111) have universality when η = 1/3. These results show that the concept of universality is also applicable to the mobilities on surface orientations different from (100). The values of η determined in this study are listed in Table 1. It should be noted that electron mobility does not necessarily have universality for E_{eff} with η = 1/2. This suggests that E_{eff} may not simply mean the average of the normal electric field within the inversion-layer.

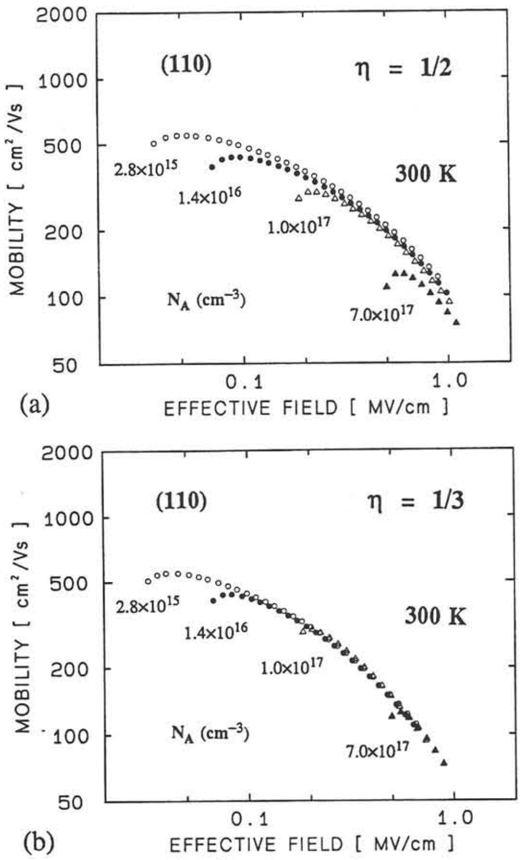

Fig.1 E_{eff} dependences of electron mobilities on (110) surface. Here, E_{eff} was defined with (a) $\eta = 1/2$ (b) $\eta = 1/3$.

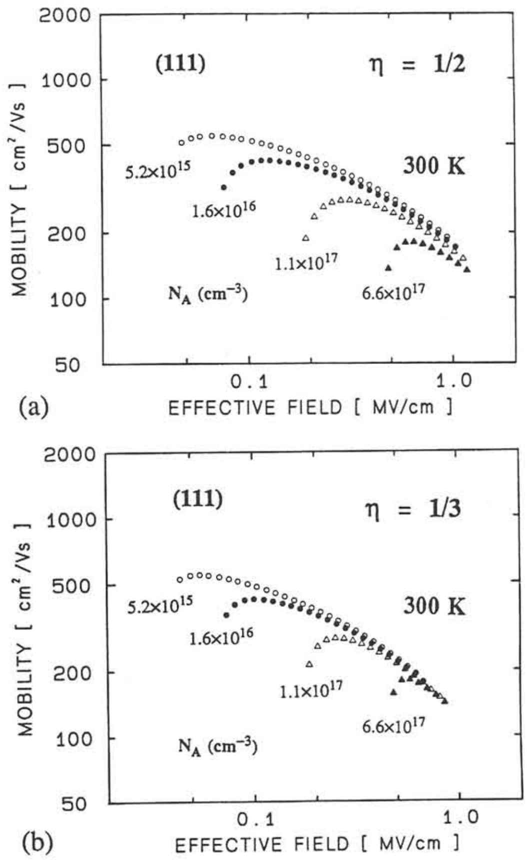

Fig.2 E_{eff} dependences of electron mobilities on (111) surface. Here, E_{eff} was defined with (a) $\eta = 1/2$ (b) $\eta = 1/3$.

Following previous theories[7,8], the mobility limited by acoustic phonon scattering is in proportion to $E_{eff}^{-1/3}$ with $\eta \sim 1/3$ under the assumption that only the lowest subband is occupied. This suggests that a multi-subband occupation of electrons on the (100) surface may cause a deviation of the value of η from 1/3. The above interpretation is consistent with the calculated results by F.Stern[9] that the occupancy of the lowest subband becomes lower in the order of (111), (110) and (100) surfaces.

3-2 E_{eff} dependences of mobilities on (100), (110) and (111) surfaces

It has been reported that the V_g dependence or E_{eff} dependence of mobility differs among surface orientations[5,6]. The cause is, however, not clear. In order to clarify the scattering mechanism which is responsible for this difference, the temperature dependences of the mobilities were studied.

As is well known, the mobility on (100) is mainly determined by three scattering mechanisms - phonon scattering, surface roughness scattering and Coulomb scattering(Fig.3). Here, phonon scattering is dominant at high temperature. As temperature decreases, surface roughness scattering and Coulomb scattering become dominant at high E_{eff} and at low E_{eff}, respectively. In this study, the authors focused on mobility in the moderate and high E_{eff} region, where Coulomb scattering becomes negligible. Then, on the basis of Matthiessen's rule, the total mobility (μ_{tot}) can be given by

$$\mu_{tot}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} \qquad (2)$$

where μ_{ph} and μ_{sr} are the mobilities limited by phonon scattering and surface roughness scattering, respectively.

Experimental results for the (100), (110) and (111) surfaces are shown in Figs.4, 5 and 6, respectively. Here, temperature was varied from 77 K to

Table 1 Values of parameter η

$$E_{eff} = (q / \varepsilon_{Si}) (N_{dpl} + \eta N_s (V_g))$$

η	(100)	(110)	(111)
ELECTRON	1/2	1/3	1/3
HOLE	1/3	—	—

447 K. Obviously, the differences in the E_{eff} dependences among surface orientations have been observed at each temperature. Furthermore, it should be noted that these differences become larger with decreasing temperature. This result means that μ_{sr} has a different E_{eff} dependence among the three surface orientations. On the other hand, as temperature increases, E_{eff} dependence seems to approach $E_{eff}^{-0.3}$ independent of surface orientations. This fact suggests that μ_{ph} has the same E_{eff} dependence. In order to examine this interpretation, μ_{sr} and μ_{ph} have been characterized more quantitatively. Figure 7 shows the temperature dependences of μ_{ph} at moderate E_{eff} (0.2 MV/cm). Then, in case of (110) and (111) surfaces, μ_{ph} was calculated from

$$\mu_{ph}(T)^{-1} = \mu(T)^{-1} - \mu(77K)^{-1} \quad (3)$$

This is because the mobilities on (110) and (111) at 77 K are approximately determined by surface roughness scattering even at 0.2 MV/cm. It has been found that μ_{ph} near room temperature is roughly proportional to $T^{-1.75}$, independent of surface orientations. As a result, μ_{ph} can be expressed by

$$\mu_{ph} = A \cdot E_{eff}^{-0.3} \cdot T^{-1.75} \quad (4)$$

where A is a constant which is weakly dependent on surface orientation.

Figure 8 shows the E_{eff} dependences of μ_{sr}. Here, μ_{sr} on (100) was deduced from

$$\mu_{sr}^{-1} = \mu(77K)^{-1} - \mu_{ph}(77K)^{-1} \quad (5)$$

using the results in Fig.7. It is clearly observed that

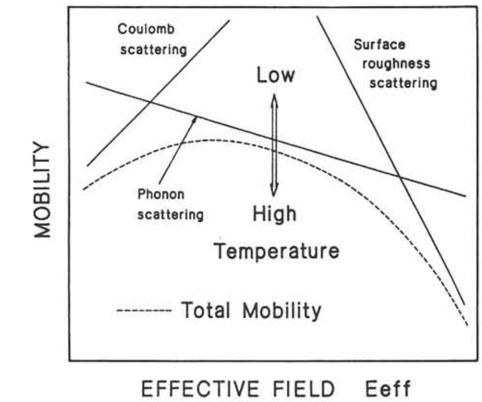

Fig.3 Schematic diagram of E_{eff} dependence of mobility by the three scattering mechanisms.

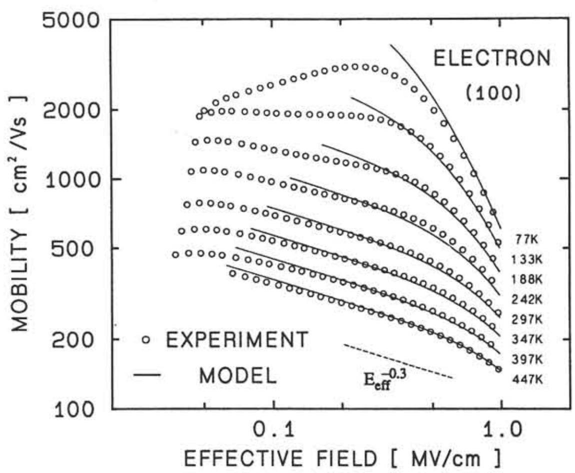

Fig.4 E_{eff} dependences of electron mobility on (100) surface in the range of 77 K to 447 K. Substrate impurity concentration is $3.9x10^{15}$ cm^{-3}. Here, E_{eff} is defined with η =1/2.

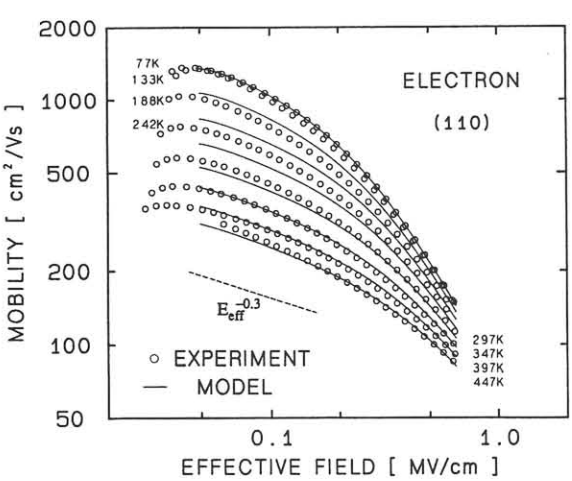

Fig.5 E_{eff} dependences of electron mobility on (110) surface in the range of 77 K to 447 K. Substrate impurity concentration is $2.8x10^{15}$ cm^{-3}. Here, E_{eff} is defined with η =1/3.

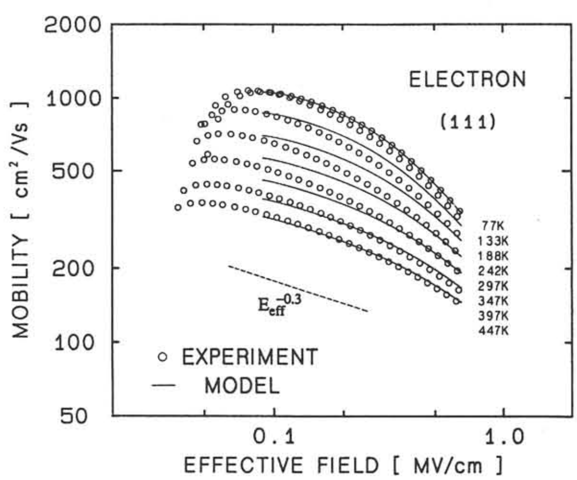

Fig.6 E_{eff} dependences of electron mobility on (111) surface in the range of 77 K to 447 K. Substrate impurity concentration is $5.2x10^{15}$ cm^{-3}. Here, E_{eff} is defined with η =1/3.

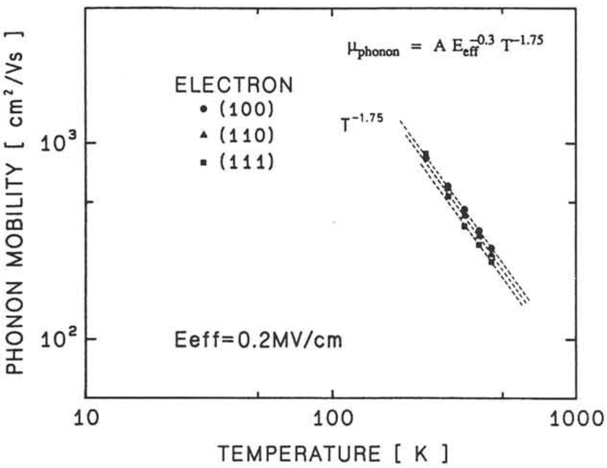

Fig.7 Temperature dependences of electron mobilities by phonon scattering (μ_{ph}) on (100), (110) and (111) at E_{eff} = 0.2 MV/cm.

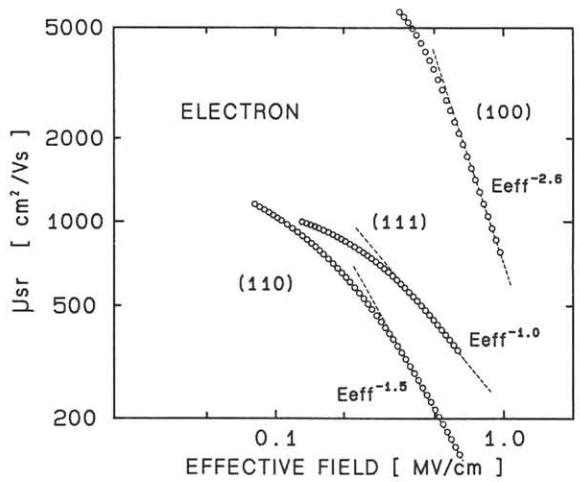

Fig.8 E_{eff} dependences of electron mobilities limited by surface roughness scattering (μ_{sr}) on (100), (110) and (111).

the E_{eff} dependence of μ_{sr} differs significantly among the surface orientations. The E_{eff} dependence becomes stronger in the order of (111), (110) and (100). This result suggests that interface roughness between Si and SiO_2 can be modulated by surface orientations, although further theoretical study is required in order to understand this difference more quantitatively.

The total mobility at each temperature can be calculated using Eq.(2). Since μ_{sr} is known to be almost non-dependent on temperature, the temperature dependence of μ_{tot} is caused by the temperature dependence of μ_{ph} shown in Fig.7. The calculated results are shown as solid lines in Figs.4-6. It has been found that good agreement between calculated and experimental values can be obtained. It is, therefore, concluded that the difference in the E_{eff} dependences among surface orientations at each temperature can be attributed to the difference in surface roughness scattering.

4. CONCLUSION

Inversion-layer mobilities on (100), (110) and (111) have been studied from the viewpoint of universality. It has been revealed, for the first time, that universality does hold for mobilities on surface orientations different from (100) if the effective field E_{eff} is appropriately defined. The E_{eff} dependence of mobility has been found to differ among (100), (110) and (111), which can be ascribed to the difference in surface roughness scattering.

ACKNOWLEDGMENTS

The authors wish to thank Drs. K.Natori, M.Yoshimi and T.Wada for their encouragements and supports throughout this work. They are also indebted to Mr. F.Umibe for reviewing and revising the original manuscript.

REFERENCES

1. A.G.Sabnis and J.T.Clemens: IEDM Tech.Dig. (1979)18
2. N.D.Arora and G.S.Gildenblat: IEEE Trans. Electron Devices, ED-34(1987)89
3. J.T.Watt and J.D.Plummer: VLSI Symp.Tech. Dig.(1987)81
4. S.Takagi, M.Iwase and A.Toriumi: IEDM Tech. Dig.(1988)398
5. T.Sato, Y.Takeishi, H.Hara and Y.Okamoto: Phys.Rev.B4(1971)1950
6. S.C.Sun and J.D.Plummer: IEEE Trans. Electron Devices, ED-27(1980)1497
7. S.Kawaji: J.Phys.Soc.Japan, 27(1969)906
8. P.J.Price: Ann.Phys.133(1981)217
9. F.Stern: Phys.Rev.B5(1972)4891