Novel Doping Profile Evaluation for 3-D MOS Transistor

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1. Introduction

To overcome the short-channel effect, three dimensional (3-D) transistor structures such as double gate structure[1], FINFET[2], beam channel transistor (BCT)[3], and corrugated-channel transistor (CCT)[4] have been developed. A schematic of CCT is shown in Fig. 1. This provides high drive current and is suitable for power transistor.

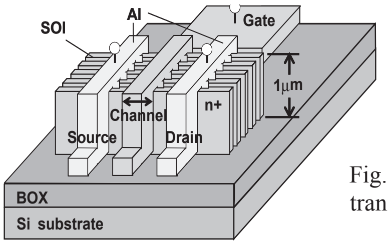

Fig. 1 Corrugated-channel transistor [4].

One key process to realize 3-D transistor is 3-D impurity doping. Using ion implantation technique, uniform sidewall doping cannot be achieved even with oblique implantation. Ununiform doping causes ununiform threshold voltage across the channel. In this sense, nearly isotropic plasma doping is better for 3-D doping[5].

Threfore, doping profile evaluation across the sidewall is essential to characterize the doping technique. In our study, plasma doping is characterized for special application to CCT with an emphasis on 3-D doping profile evaluation even with an adverse effect of sputtering.

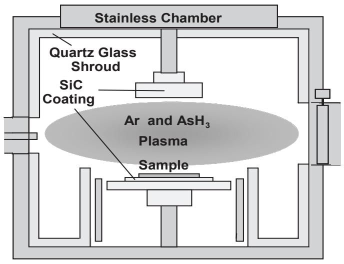

Fig. 2 Plasma doping apparatus.

2. Experimental

Schematic diagram of a plasma doping apparatus used in this study is shown in Fig. 2. Plasma is discharged with 13.56-MHz RF power supply and minus bias is applied by direct current. Doping gas was a mixture of Ar and AsH_3 at 2 - 4 Pa and the post anneal temperature was 900°C.

Sheet resistance of plasma doped samples as a function of arsenic dosage is shown in Fig. 3. "Calculated Dose" is evaluated by total substrate current. Approximately 1 % of the substrate ion current is effective as dopants. This may be mainly caused by sputtering and idle current into substrate.

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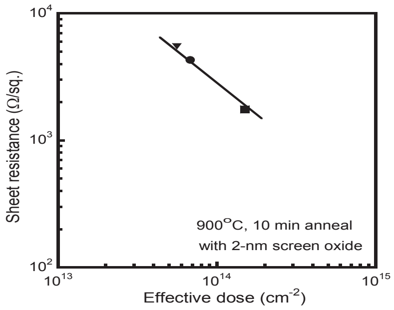


Fig. 3 Sheet resistance vs As dosage evaluated by SIMS profile.

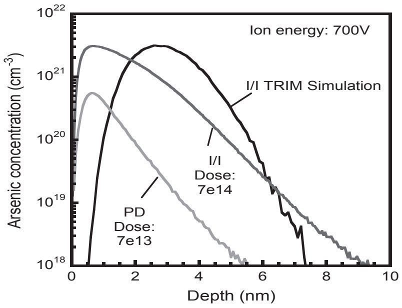


Fig. 4 SIMS profiles of plasma doping (PD) and ion implantation (I/I).

SIMS profiles of plasma doping are shown in Fig. 4 as compared with those of ion implantation. The 2-nm screen oxide does not affect the doping profile. The screen oxide is removed before SIMS measurement.

Then, doping profiles are evaluated as follows. The structures are formed by anisotropic etchant of 2.5-% TMAH at 75°C. Then, plasma doping is performed. An SEM image after doping is shown in Fig. 5. The BOX-SiO_2 layer is under etched by subsequent HF solution treatment. It is observed the upper part is sputtered. It is estimated that enhanced electric field causes the sputtering at the upper edges. Sputter angle dependence is measured and shown in Fig. 6. Here, angle of perpendicular to the substrate is defined to be 0 degree. Almost the same phenomenon was reported in case of plasma CVD[6].

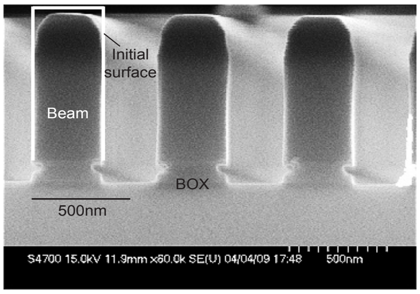


Fig. 5 Cross-sectional SEM photograph of plasma-doped comb shaped structure.

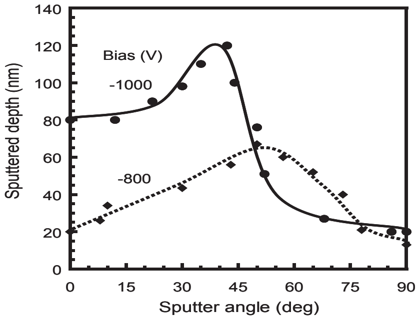


Fig. 6 Angle dependence of sputtering depth.

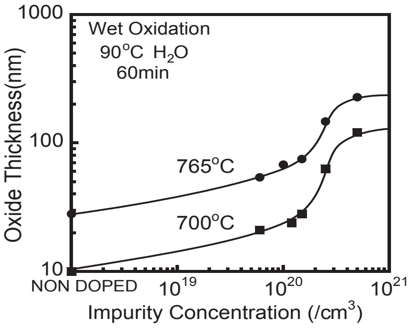


Fig. 7 Imputiry Enhanced Oxidation.

Since there has been few effective method to evaluate 3-D doping profiles, an indirect evaluation method utilizing impurity-enhanced oxidation (IEO)[7] which is enhanced in lower temperature is developed in this study.

Obtained data of IEO are shown in Fig. 7. Since the upper surface of comb-shaped structure is (110) and a sidewall surface is (111), it is necessary to take into consideration the difference in the oxidation rate by orientation. An Arrheniusplot of oxidation rate of (111) and (110) is shown in Fig. 8.

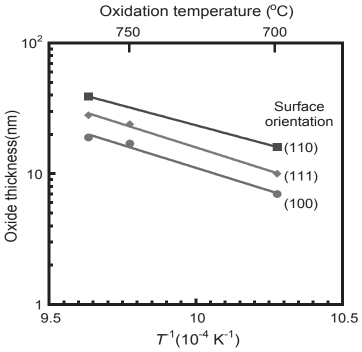
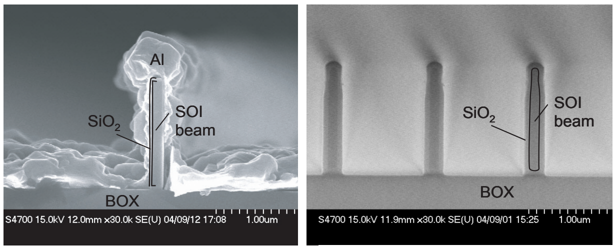


Fig. 8 Arrhenius plot of impurity enhanced oxidation, IEO.



(a) Non-doped

(b) Plasma-doped

Fig. 9 Cross-sectional SEM photographs for oxidized comb-shaped structures.

Oxidized, doped comb-shaped structure is shown in Fig. 9 (a). Compared with oxidized, non-doped comb-shaped structure is shown in Fig. 9 (b). It is shown that oxidation rate is increased obviously for doped structures. Considering the dependences of impurity concentration and crystal orientation, 3-D doping concentration is evaluated as shown in Fig. 10. In Fig. 10 oxide thickness dips are clearly observed at the top and the bottom portions of non-doped beam. This may be caused by stress[8]. Thus, doping concentration evaluation becomes slightly inaccurate for sharp edges.

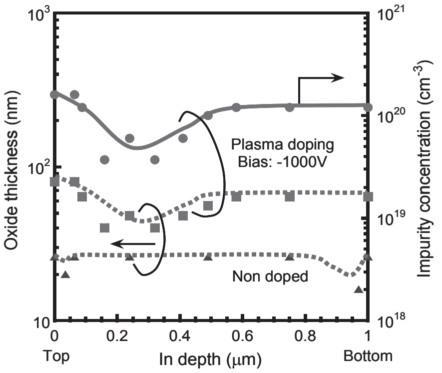


Fig. 10 In-depth doping concentration evaluated by the method proposed.

3. Conclusion

Plasma doping is carried out to comb-shaped structure of 1-μm height and 50-500-nm width. It is observed that sidewalls are doped uniformly at about 5×10^{19} cm^{-3}, though top edges are doped at several times higher concentration. Thus a doping profile estimation method utilizing impurity-enhanced oxidation (IEO) is successfully developed. While, an adverse effect of anomalous edge rounding due to sputtering is found. Plasma doping should be carried out coping with this sputtering effect.

Acknowledgements

This work was partly supported by Grant-in-Aids for Scientific Research (B#12555102, A(2)#13025232) from the Ministry of Education, Science, Sports, and Culture, Japanese Government.

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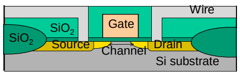
Background

- Planar MOS structure



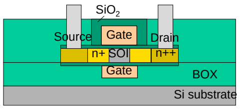
Conventional MOSFET

High performance
= further scaling

Conventional planar:
short channel effect

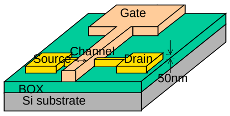
New structure:
Three dimensional
(3-D) structure

- 3-D structures reported



Double gate SOI MOSFET

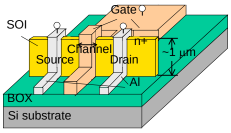
- Process complexity



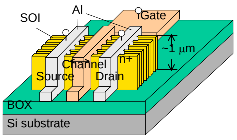
FinFET

- Planar process compatibility

Beam-Channel Transistor



Beam-channel transistor

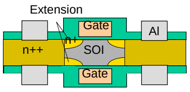


Corrugated-channel transistor

Larger drive current
per unit planar area

Key process: 3-D impurity doping

Source and drain (S/D) fabrication



beam (top view)

S/D formed by $POCl_3$ gaseous doping
Extension formed by plasma doping (PD)
|
controlled S/D region

plasma doping characterization
for 3-D MOS transistor

S/D Formation

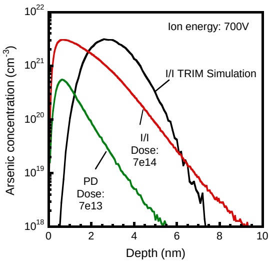
Estimated applicability to 3-D doping

Doping method	Merit	Demerit
Gaseous doping	•High dosage •Uniform doping	•Poor low-dosage controllability
Ion implantation	•High controllability for dosage	•Complexity of oblique and multi-time implantation
Plasma doping	•Dosage controllability •Uniform doping	•Fair low-dosage controllability

S/D formed only $POCl_3$ gaseous doping
- Short channel effect
- Increased parasitic resistance

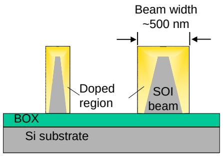
Evaluation Method of Doping Profile

Evaluation for Doped Planar Substrate
SIMS profiles



Plasma doping: Effective dose = 1 %
Shallower depth
|
Dopants come from various directions

3-D structure -> difficult to evaluate



No effective method to evaluate doping profile on sidewall
|
New method

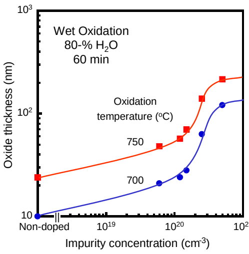
Impurity-enhanced oxidation

Oxidation rate differs with
impurity concentration of doped Si surface
at low temperature wet oxidation

Impurity-Enhanced Oxidation

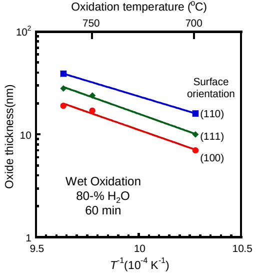
Impurity-Enhanced Oxidation

Wet oxidation: gases are O_2 and H_2O (at 90°C)



Impurity concentration evaluation
1. Oxidation of doped sample
2. Measurement of oxide thickness

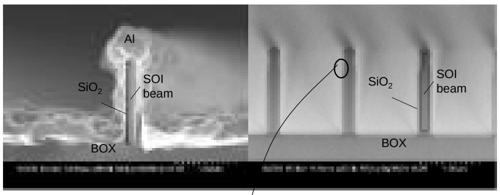
Arrhenius plot of oxidation rate of orientation



- Oxidation rate ratio of (110) / (111)
1.6 (700°C)、1.4 (765°C) at wet oxidation
1.14(850°C)、1.08(1000°C) at dry oxidation

Evaluation of In-Depth Doping Concentration

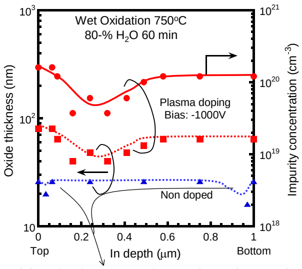
Oxidized Corrugated-Channel Structure



Non-doped	Doped
Wet oxidation 750°C 60 min	plasma doping bias = -1000 (V) Wet oxidation 750°C 60 min
T_{ox} = 25 nm	T_{ox} = 60 nm

Oxide at the edge under the top surface is thin at doped sample
|
sputtering caused by electric field concentration of plasma

Evaluated by the method proposed

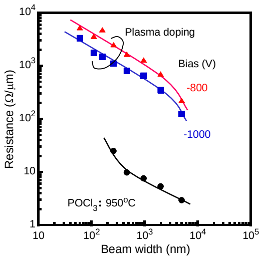


Oxide of edge part of non doped sample was thinned by stress and profound at low temperature oxidation
|
Slightly inaccurate for sharp edges

Beam Resistance Evaluation

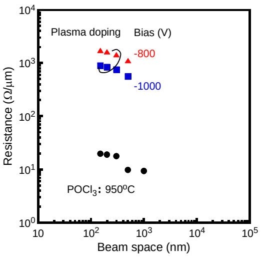
Comparison between plasma doping and $POCl_3$ gaseous doping

Beam width dependence
of resistance at single beam



As compared with $POCl_3$, resistances with plasma doping are about 50 times higher

Beam space dependence of
Resistance at 460-nm beam width

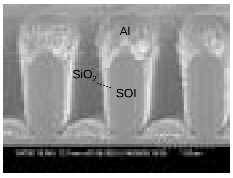


Narrower space causes
less doping

Doping Profile Evaluation by IEO

Evaluated in-depth doping concentration
of POCl3 gaseous doping and plasma doping

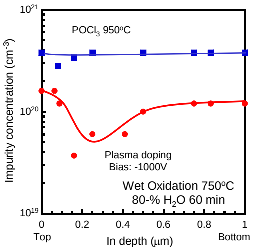
Wet oxidation 750°C 60 min



Phosphorus gaseous doping
950°C diffusion 10 min /
anneal 3 min

Uniform doping

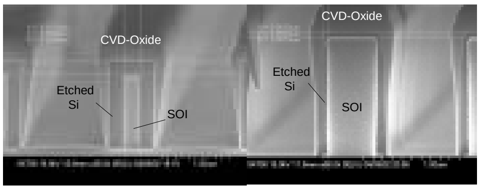
Edge part of oxide
was thinned by tress



Phosphorus gaseous doping
|
highly doped

Doped Region Uniformity Evaluation by Preferential Etching

Si etchant HF : HNO_3 (1 : 60) 10 sec



Phosphorus gaseous doping 950°C diffusion 10 min / anneal 3 min	Plasma doping bias = -1000V anneal 1000°C 10 sec
•x_j ~ 200 nm	•x_j ~ 60 nm

Compared with POCl3 gaseous doping,
plasma doping formed very shallow junction

Conclusion

1. Plasma doping is carried out for corrugated-channel structure
2. Sidewalls are doped uniformly at about $1x10^{20} cm^{-3}$ by plasma doping
3. A doping profile estimation method utilizing IEO is successfully developed
4. Comparison between plasma doping and $POCl_3$ gaseous doping
   Those characteristics are as follows
   Gaseous: higher concentration and deeper doping
   Plasma: comparatively low concentration and shallow doping

Acknowledgements
This work was partly supported by Grant-in-Aids for Scientific Research (B#12555102, A(2)#13025232) from the Ministry of Education, Culture, Sports, Science and Technology, Japanese Government.

COE Workshop 3rd, 2004
Dec. 6 Hiroshima Univ., Japan