Workfunction Tuning Technique for Dual-Gate CMOS with Single Metal Gate

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1. Introduction

Gate oxides for leading edge production MOS devices, which are the most important factor for improving the performance of FETs, are becoming thinner than 1.5 nm. As the gate oxide is scaled, the increase in electrical thickness due to gate depletion becomes more severe. The total loss in electrical thickness due to gate depletion and quantum effects in a channel is estimated to be about 0.7 nm. This value is too large compared with physical equivalent oxide thickness. A metal gate will relieve this loss about by half. Refractory metals, such as Mo, Ta, Ti, and W, and their nitrides are candidates for metal gate materials. Their workfunction and melting point are shown in Fig. 1. Their robustness against high-temperature processes like S/D activation annealing is necessary feature as a gate electrode material. However, for CMOS devices application workfunction of metal gate must be adjusted to that for p^+-poly-Si or n^+-poly-Si.

In this report, evaluation of Mo workfunction tuning technique and brief prospect are described.

2. Mo workfunction tuning with Nitrogen

Wakabayashi et al. [1] reported workfunction tuning of TiN by N^+ implantation. This method was based on composition tuning by high dose N^+ implantation. Because of narrow tuning width, this method is not practical. Ranade et al. [2] reported Mo workfunction tuning also by N^+ implantation with negligible composition change. We have evaluated influences of N^+ implantation on interfaces and gate oxides [3].

Figure 2 shows fabrication process flow of Mo gate MOS diodes. MOS diodes with various oxide thickness were fabricated for one N^+ implantation condition to extract workfucntion and fixed charge density from C-V characteristics. The workfunction obtained by this method is noted as apparent workfunction in this report. RTA at 900°C for 1 min was carried out after N^+ implantation. The apparent workfunction did not depend on RTA condition. Figure 3 shows the extracted apparent workfunction. N^+ implantation dose was 2.5×10^{15} cm^{-2}. Implantation depth was varied by implantation energy and angle. In the case of no N^+ implantation Mo showed the apparent workfunction equivalent to p^+-poly-Si. As the implantation depth becomes deeper the apparent workfunction shifted lower. However, interface and oxide damage were observed in deep N^+ implanted specimens, as shown in Figs. 4 and 5. C-V characteristics for such MOS diodes in Fig. 4 shows humps that imply interface state generation. Gate leakage current increased as the N^+ implantation became deeper. Figures 5 and 6 show nitrogen profiles in Mo and Si, respectively. 25 keV N^+ implantation that was effective for apparent workfunction tuning leads to N^+ implantation into Si substrates through gate oxides. The implanted nitrogen in Mo diffuses very fast during RTA and forms nearly uniform profile as shown in Fig. 6. The most part of nitrogen in Si disappears after RTA, as shown in Fig. 7, that implies oxinitride formation at the SiO_2/Si interface. We have tried optimizing shallow implantation condition to obtain workfucntion shift without these influences by nitrogen, however, it was not successful to date.

3. Direction to future research

From an application view point, effectiveness of the N^+ implantation should be evaluated by MOSFET V_{th} shift and channel mobility. Ranade et al. [4] reported MOSFET with N^+ implanted Mo showed reasonable V_{th} shift, however they recently commented that mobility degradation is caused by the N^+ implantation. Figure 8 shows C-V characteristics of TiN capped Mo MOS diodes. Apparent workfunction shift was also obtained by nitrogen thermal diffusion from TiN. The TiN/Mo MOS diodes showed no degradation found in the N^+ implantation cases. However, recently we found that the apparent workfunction shift in a TiN/Mo structure was reversible by additional thermal process after removing TiN. These results indicate that nitrogen transported by thermal diffusion is not stable at the Mo/SiO_2 interface and easily diffuse out. On the contrary, nitrogen introduced by the N^+ implantation was stable at the interface because additional thermal treatment did not affect. However, the N^+ implantation involved the counter effects. In general, if we can fabricate a stable atomic layer at the metal/insulator interface, workfunction shift due to electric dipole formation is expected. Impurity pileup caused by thermal treatment has possibility to match this claim. Snowplow effect due to silicidation is a considerable candidate [5].

4. Summary

We have evaluated Mo workfucntion tuning by N^+ implantation and nitrogen thermal diffusion. The former showed large apparent workfucntion shift, however, damage due to the implantation was not negligible. The later also showed the apparent workfucntion shift but it was not thermally stable. These methods should be improved or other methods should be found to apply workfucntion tuning technique to practical devices.

References

1. H. Wakabayashi et al. 1999 IEDM Tech. Digest p. 253.
2. P. Ranade et al , MRS. Proc., **611** (2000) p. C3.2.1.
3. T. Amada et al., MRS Proc., **716** (2002) p. 299.
4. Q. Lu et al , Digest 2001 VLSI Tech. Symp. p. 45.
5. W.P. Masazara et al, 2002 IEDM Tech. Digest p. 367.

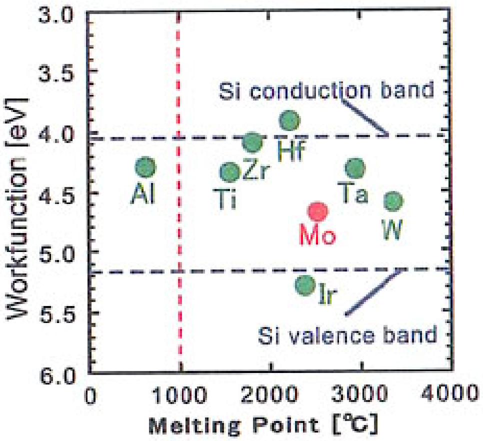

Fig. 1 Workfunction and melting point of metal materilas.

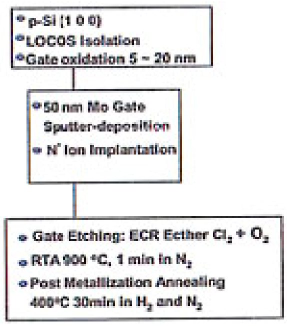

Fig. 2 Fabrication process flow of MOS diodes for workfunction evaluation.

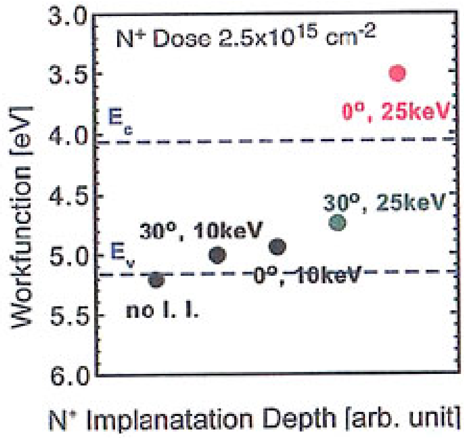

Fig. 3 Workfunktion extracted from Mo gate MOS diodes with N^+ implantation.

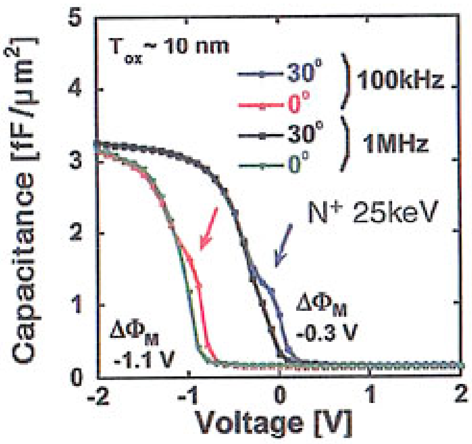

Fig. 4 Influence of N^+ implantation on Mo gate MOS diode C-V characteristics.

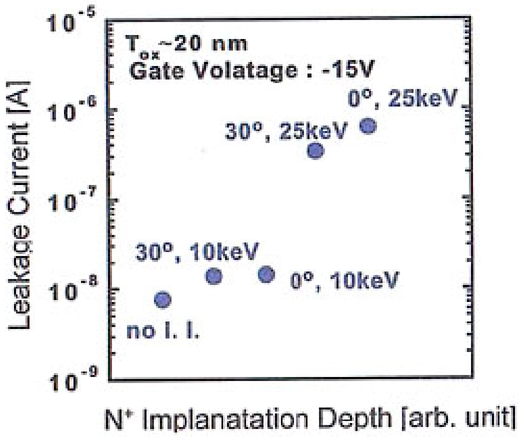

Fig. 5 Leakage current enchanced by N^+ implantation in Mo gate MOS.

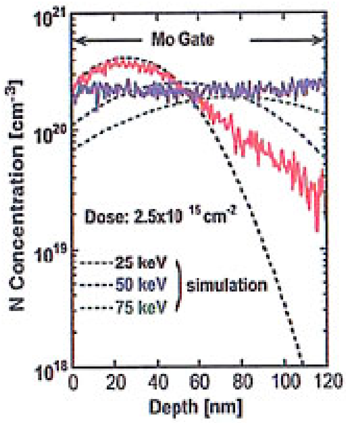

Fig. 6 Nitrogen depth profiles in Mo obtained by SIMS (solid lines) and simulation (dashed lines).

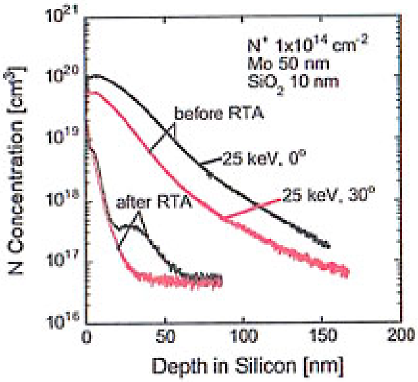

Fig. 7 Nitrogen SIMS depth profiles in Si substrates for before and after RTA. RTA temperature and time were 900°C and 1 min, respectively.

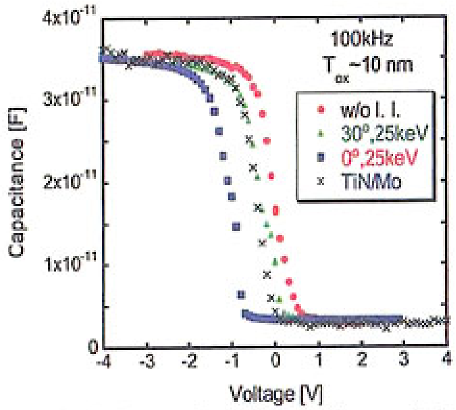

Fig. 8 Comparison of C-V characteristics for a TiN/Mo gate diode with that for N^+ implanted diodes.

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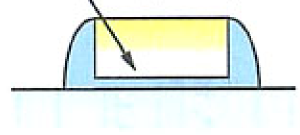
Necessity of the Metal Gate and Required Property

Poly-Si gate

Issues
- High resistivity
- Boron penetration
- Gate depletion

Effective Oxide Thickness increases by the gate depletion

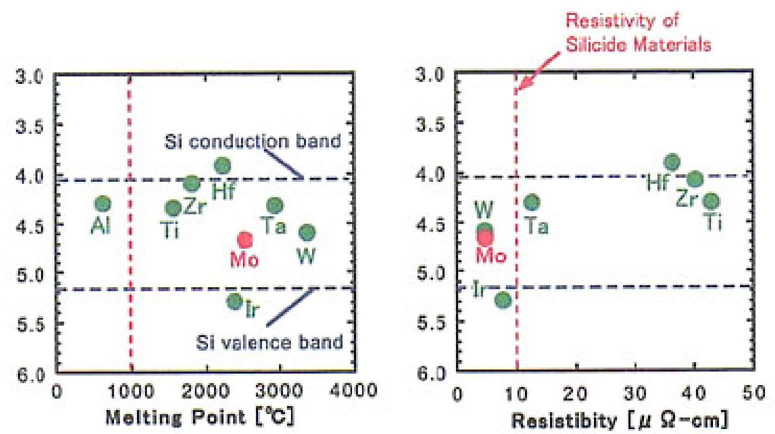


Metal gate

Required property
- High melting point
- Low resistivity
- Suitability for the convention processes
- Dual work function

Dual-Metal Gate
nMOS : Low Φ_M (~ 4.0V)
pMOS : High Φ_M (~ 5.0V)

Workfunction and Resistivity of Metals



Work Function Tuning Technique

Dual metal will make fabrication process complicated
Dual work function with single metal is necessary

Work Function Control Technique

P.Ranade et al,(UCB), MRS 2000 Spring Meeting

Mo gate

Work function changed under the specific condition of annealing and N implantation

		Annealing temperature [°C]	
	N^+ implantation	RT	700
Work function [eV]	$5x10^{15}cm^{-2}$	-	4.03
	None	4.42	5.10

Our study

Influence of N^+ implantation on MOS characteristics

Work Function
- C-V

Leakage Current
- I-V

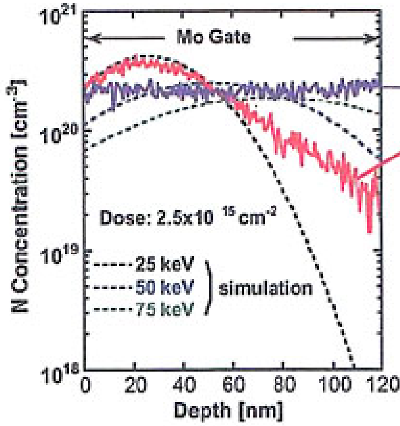
Typical Diode Fabrication Flow

- p-Si (1 0 0)
- LOCOS Isolation
- Gate oxidation 5 ~ 20 nm

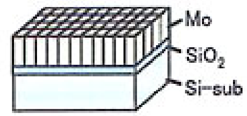
- 50 nm Mo Gate Sputter-deposition
- N^+ Ion Implantation

- Gate Etching: ECR Ecther $Cl_2 + O_2$
- RTA 900 °C, 1 min in N_2
- Post Metallization Annealing 400°C 30min in H_2 and N_2

SIMS Depth Profile in Molybdenum



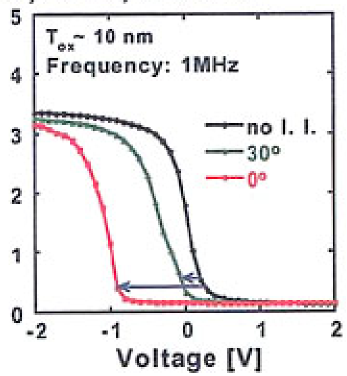
After annealing
As ion implanted
Channeling?
or
SIMS Artifact?
25 keV

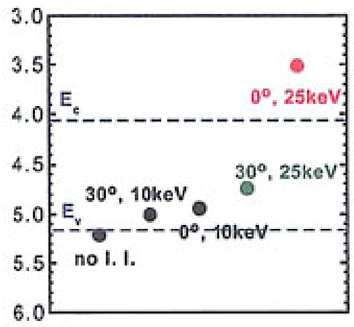


Mo has a columnar structure

C-V Characteristic andWork Function

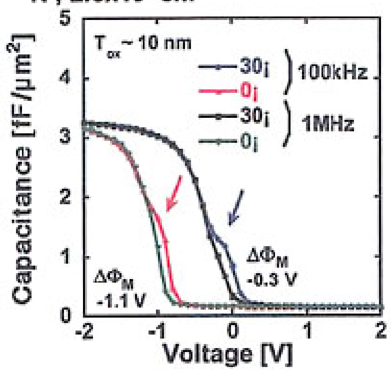
Implantation Condition:
N^+, 25 keV, $2.5x10^{15}cm^{-2}$





Effect of Interface States

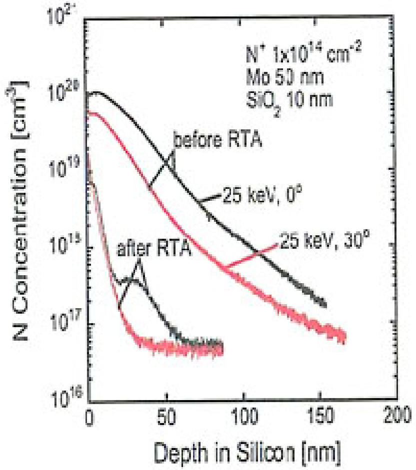
Implantation Condition:
N^+, $2.5x10^{15}cm^{-2}$



Large Φ_M shift

Increase in interface states

SIMS Profile: After Annealing



Implantat Energy 25 keV

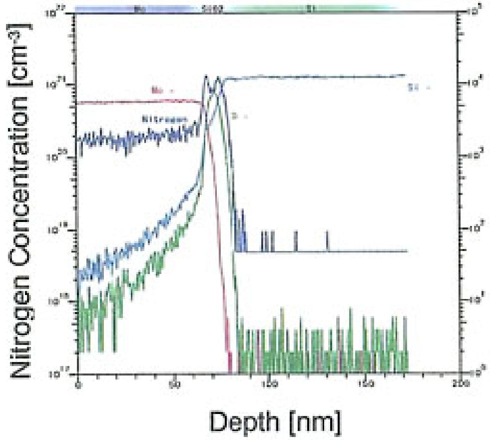
- **Surface Nitrogen concentration**
  0° : 1x10^{20} cm^{-3}
  30° : 6x10^{19} cm^{-3}

Implantat Energy 10 keV

- **Less than adsorped Nitrogen**

- **Influence of Nitrogen as a donor should be evaluated**

Nitorgen at Interfaces

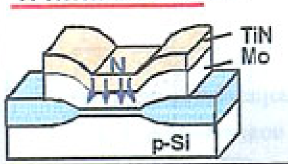


Nitrogen

at Mo/SiO$_2$ Interface
-> Workfunction shift

at SiO$_2$/Si Interface
-> SiON formation
-> Gate leakage current
Interface State

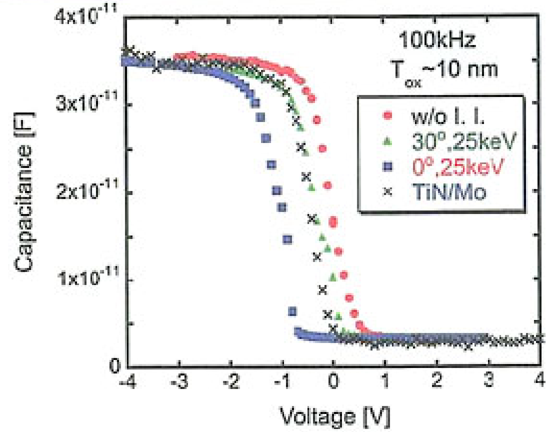
Another Method: N Diffusion from TiN on Mo



- Mo Sputtering 50 nm
- TiN Sputtering 40 nm
- RTA 800°C, 1 min
- TiN/Mo Gate Patterning

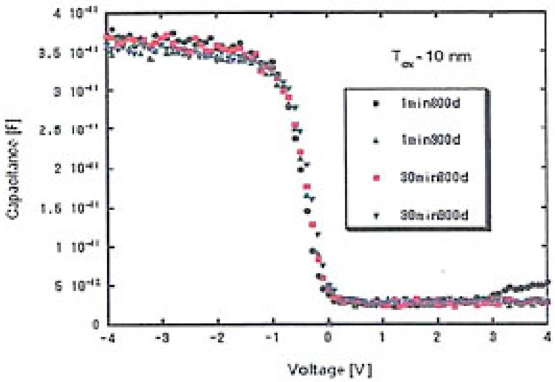
Softer nitrogen introdcution into Mo

MOS Diodes C-V: TiN/Mo and Others



TiN/Mo: No hump in C-V, No increase in leakage current

Issues of Diffusion from TiN/Mo



Diffusion time, temperature and N composition in TiN
-> Not Effective for Φm Control
Thermally Reversible

Summary

- Work function control by N^+ implantation in Mo gate MOS structure
  - Φ_M shift from 5.2 eV to 4.0 eV
    Surface Nitrogen concentration ~ $1x10^{20}cm^{-3}$
    - Problems: Leakage current and interface states
    → More detailed evaluation of the Mo/ SiO_2 / Si interfaces is necessary
- Solid Phase Diffusion from TiN: less Damage
  How to change workfunction shift?

Other Methods?

Keywords: Pileup of Impurities
Where?: Metal/Insulator Interface
ex. Snowplow effect during silicidation

What elements?
Any elements stable at the interface
-> electric dipole formation and Φm shift

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