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Multi-V_T with metal gate work-function modulation by PLAD implants for Ge FinFET applications

S. Kothari[1], H. Nejad[2], N. Variam[2] and S. Lodha[1]

[1] Dept. of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India
[2] Applied Materials Inc., Gloucester, MA, USA 01930-2297
E-mail: slodha@ee.iitb.ac.in

Abstract

This work demonstrates muti-V_T for TiN/HfO_2 gate stack on Ge using plasma assisted doping (PLAD) for Ge FinFET applications. By varying implant species, dose and energy we demonstrate effective TiN work-function (WF) modulation from near midgap to near valence band edge (PLAD O_2 (60-80 mV) and N_2 (160-180 mV)) and near conduction band edge (PLAD Arsenic (130-280 mV)) of Ge. Low energy PLAD process offers wide range of effective WF tuning covering entire bandgap of Ge. To study the impact of implant, essential gate stack parameters (effective oxide thickness (EOT), interface quality (D_{it}), gate leakage (J_g) and TiN resistance) are evaluated for different species (N_2, O_2 and As) using various material and electrical characterization techniques. It is also observed that the interfacial dipoles at the TiN/HfO_2 interface govern the effective WF modulation.

1. Introduction

Due to its higher carrier mobilities than Si [1], Germanium is being considered as a channel material for future high performance FinFET CMOS technologies [2]. However, threshold voltage (V_T) tuning using process modifications for both n and p-FinFET devices (Fig. 1 (a) and Fig. 1 (b)) is one of the most fundamental requirements for FinFET technology. Various studies on Si FinFETs [3] have been reported but similar reports for emerging high mobility channel materials such as Ge are sparse.

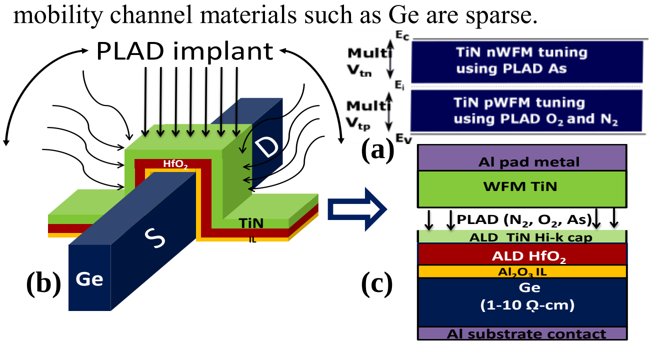

Fig. 1 (a) Desired WF modulation by varying PLAD species, dose and energy conditions for Ge CMOS technology, (b) Schematic showing PLAD implant used for V_T tuning of a Ge FinFET, (c) Cross-section schematic of MOSCAP devices with Al_2O_3 interfacial layer (IL) used in this work.

In this work, we have employed plasma assisted doping (PLAD) process with different species, dose and energy to tune the effective work-function (WF) of ALD TiN metal from near midgap to near band edges of Ge. PLAD O_2 and N_2 processes tune the effective WF towards valence band edge of Ge over a range of 60 mV-180 mV. On the other hand PLAD As can tune the effective WF towards the conduction band edge of Ge over a range of 130 mV-280 mV. Flat band voltage shifts (ΔV_{fb}) were measured by fabricating MOS capacitors (EOT~2 nm) with different implanted species in TiN cap. The study is further extended and compared based on various gate stack performance metrics (effective oxide thickness (EOT), density of interface states (D_{it}), gate leakage (J_g) and TiN resistance). It is also observed that in order to get maximum ΔV_{fb} irrespective of the species, the implant dose and energy condition should be optimized such that TiN/HfO_2 interface has maximum concentration of implanted species. The interfacial dipole at TiN/HfO_2 interface changes the effective WF [4]. PLAD N_2 data from Ref. [4] is used for comparison.

2. Experimental details

MOS capacitors (MOSCAPs) were fabricated on n, p-Gewafers ((100), 1-10 Ohm-cm) using the process flow described in [4]. Fig 1(c) shows a cross-section schematic of the Ge gate stack indicating PLAD of different species (As, N_2, O_2). The effect of implant is studied with reference to a non- implanted control sample.

3. Results and Discussions

Fig. 2 shows a dose dependent ΔV_{fb} of the implanted samples w.r.t the non-implanted sample for different PLAD species. As shown in Fig. 2(a) ΔV_{fb} is positive for PLAD O_2 and N_2 (effective WF tuning towards valence band edge of Ge). On the other hand PLAD As (Fig. 2(b)) has negative ΔV_{fb} (effective WF tuning towards conduction band edge of Ge). Inset of Fig. 2 shows the raw C-V data indicating the V_{fb} shift. Fig. 3(a) shows the SRIM profile of implanted (dose=$2x10^{15}$ cm^{-2}) O_2, N_2 at 0.2 keV and As (inset) at 2 keV. The energy and TiN cap thicknesses (2 nm and 5 nm for As and 1 nm for O_2 and N_2) were optimized such that implanted species has maximum concentration at the TiN/HfO_2 interface. Fig. 3(b) shows the XPS spectra for As3d and TiON component of O1s spectra (inset) w. r. t non-implanted sample. Results from four probe resistivity measurements are shown in Fig. 4(a). TiN resistivity can vary with factors such as deviations from the stoichiometric ratio of Ti/N, crystallinity, grain size, vacancies and defects. Fig. 4(b) shows the near-midgap D_{it} for the MOS-

CAPs measured using frequency-dependent conductance measurements at room temperature. As seen from SRIM profiles (Fig. 3(a)) low energy PLAD implant process does not degrade the IL/Ge interface and hence the D_{it} value for implanted samples are similar to the non-implanted sample.

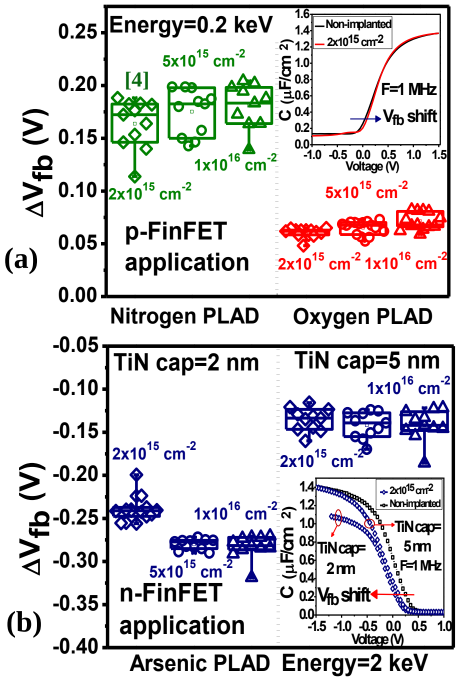

Fig. 2 Measured ΔV_{fb} of implanted samples w. r. t the non-implanted samples (a) PLAD N_2 [4] and O_2 (effective WF increasing), (b) PLAD As (effective WF decreasing). Inset shows the raw C-V data indicating V_{fb} shifts.

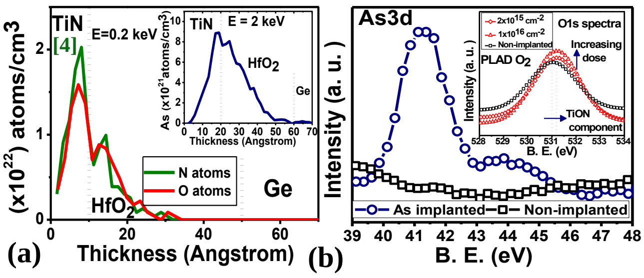

Fig. 3 (a) SRIM for fixed dose (2x10^{15} cm^{-2}) N_2, O_2 and As (inset) implants, (b) XPS spectra for As3d and TiON component of O1s spectra (inset).

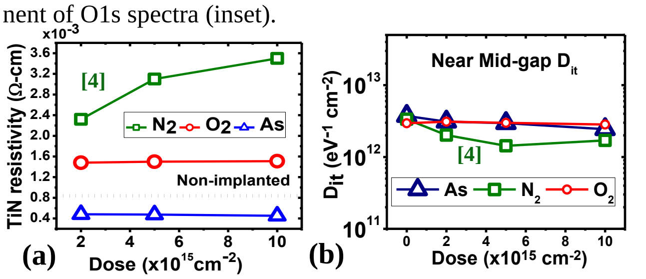

Fig. 4 (a) Four probe TiN resistivity data for implanted sample w. r. t non-implanted sample, (b) Near-midgap D_{it} for the MOSCAPs measured using frequency-dependent conductance measurements at room temperature.

Fig. 5(a) shows J_g vs gate voltage for the non-implanted and implanted samples for varying dose and species. EOT data extracted from C-V characteristics and a calibrated, self-consistent 1D Schrodinger-Poisson C-V simulator is also indicated. As expected, due to the low implant energy (0.2 keV), there is no change in EOT (inset of Fig. 2(a)). Also there is no increase in J_g post-implant for O_2 and N_2 PLAD (Fig. 5(a)) attributed to large band offset of Al_2O_3 IL w.r.t Ge. On the other hand high implant energy (2 keV) for As causes EOT degradation (inset of Fig. 2(b)) and increase in J_g for TiN cap thickness of 2 nm (Fig. 5(a)). However, for TiN cap thickness of 5 nm, these parameters are intact at the expense of lower V_{fb} shifts vs TiN cap thickness of 2 nm (Fig. 2(b)). Further studies are required for optimization of energy and TiN cap thickness.

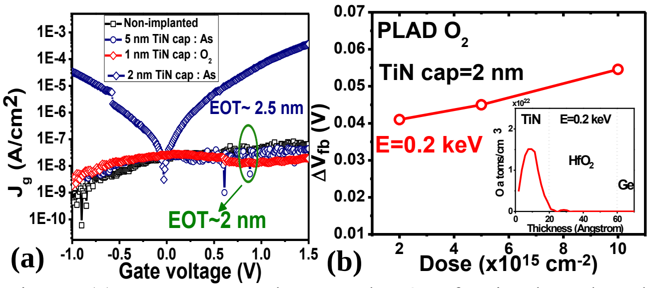

Fig. 5 (a) J_g vs gate voltage and EOT for implanted and non-implanted Ge gate stacks. No J_g and EOT degradation is observed for PLAD As with TiN cap of 5 nm, (b) Measured V_{fb} shifts for implanted dose farther away from interface. Inset shows the SRIM profile for the same.

Fig. 5(b) shows ΔV_{fb} for thicker TiN cap (2 nm) for PLAD O_2. It is observed from SRIM profile (inset) that the implanted dose is farther away from TiN/HfO_2 interface as compared to SRIM profile in Fig. 3(a). Lower ΔV_{fb} is obtained for this case which implies that interfacial dipoles at TiN/HfO_2 interface govern the effective WF modulation. The same model is also valid for PLAD As for TiN cap thickness of 2 nm vs 5 nm as shown in Fig. 2(b).

4. Conclusions

In summary we report effective WF tuning over entire bandgap of Ge in metal gate stacks on Ge using low energy PLAD implants (different species). With no degradation of EOT, gate leakage and D_{it}, and a small change in resistivity, this process can help in realizing a multi-V_T Ge FinFET CMOS technology. PLAD process offers wide range of effective WF tuning by varying implant dose, energy, implant species and TiN cap thickness. Interfacial dipoles at TiN/HfO_2 interface govern the effective WF modulation.

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