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To cite this version:

Thomas Signamarcheix, Frédéric Allibert, Fabrice Letertre, Thierry Chevolleau, Lesly Sanchez, et al.. Germanium oxynitride (GeOxNy) as a back interface passivation layer for Germanium-on-insulator substrates. Applied Physics Letters, 2008, 93 (2), pp.022109. 10.1063/1.2960345 . hal-00387508

HAL Id: hal-00387508

https://hal.science/hal-00387508v1

Submitted on 13 Dec 2022

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Germanium oxynitride (GeO_xN_y) as a back interface passivation layer for Germanium-on-insulator substrates

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(Received 17 April 2008; accepted 24 June 2008; published online 17 July 2008)

This paper describes the development of a GeO_xN_y surface passivation of germanium, which is mandatory for microelectronics germanium-on-insulator (GeOI) substrate fabrication. Indeed, germanium surface reactivity in ambient atmosphere requires the development of Ge surface passivation in order to provide an electrically acceptable interface between the active layer and the buried oxide (BOX) of GeOI substrates. In this paper, GeOI substrates with a passivation interlayer between the Ge film and the BOX were fabricated using the Smart Cut™ technology. Plasma treatments produced a germanium oxynitride (GeO_xN_y) passivation interlayer with a nitrogen concentration up to 40% and thickness of 3 nm. Electrical activity in such GeOI active layer was investigated with pseudo-metal-oxide-semiconductor field effect transistor measurements. Electron mobility reaches a value of 670 $cm^2 V^{-1} s^{-1}$, notably higher than those typically reported on nonpassivated GeOI structures. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2960345]

Germanium is intensively studied as alternative channel material of metal-oxide-semiconductor field effect transistor (MOSFET) devices due to its transport properties. Nevertheless, the interactions between Ge and the gate dielectric are limiting the electrical performances. As a consequence, surface passivation engineering is required for any dielectric that might be selected, such as SiO_2,[1] ZrO_2,[2] Al_2O_3,[3] or HfO_2.[4] Different approaches exist for surface passivation such as a thin silicon cap[5,6] or germanium oxynitride (GeO_xN_y).[7,8] To date, silicon cap layer allowed the demonstration of record *p*-MOS devices,[9] but GeO_xN_y interlayer also demonstrated promising properties especially for *n*-MOS devices.[10] This Ge oxynitridation is usually achieved through either the thermal nitridation of a GeO_x layer under NH_3,[10] or plasma treatments using N_2 precursor.[11]

The application of Ge to sub-22 nm fully depleted devices requires the introduction of germanium-on-insulator (GeOI) structures because they combine Ge and "on-insulator" advantages (improved parasitic capacitances and electrostatic control). For such structures, the properties of the Ge buried oxide (BOX) interface (hereinafter called back-interface) are critical because they strongly influence top surface MOS devices. GeOI structures with high hole mobility ($\mu_p = 300$ $cm^2 V^{-1} s^{-1}$) have been previously reported by our group.[2] In this letter, we focus on the improvement of the conduction in the inversion mode in the GeOI layer. Electrical properties were investigated using pseudo-MOSFET measurements that are well suited for vertically isolated thin films.[13]

GeOI substrates were fabricated using the Smart Cut™ technology, following a process we previously reported elsewhere.[14] Donor wafers were 2.5 μm thick Ge epilayers grown by chemical vapor deposition on 200 mm Si(100) substrates,[15] with *p*-type residual doping and low threading dislocation density in the 6×10^6 cm^{-2} range. The full layer transfer sequences were performed below 600 °C temperature to minimize uncontrolled reaction between Ge and oxygen. GeOI structures consisted of a 90 nm thick Ge film on a 200 nm thick SiO_2 BOX. A GeO_xN_y interlayer was introduced between the Ge active film and the BOX. High reactive-species density plasma processes were developed in an Inductively coupled plasma (ICP) reactor to generate the thin Ge oxynitride layer using ion dominant nitridation.

Binding state configurations of the Ge atoms in the oxynitride were evaluated using X-ray photoelectron spectroscopy (XPS) in quasi *in situ* conditions thanks to a low-pressure transfer chamber (3 mTorr, N_2 ambient) between the plasma reactor and the XPS chamber. Figure 1 shows the XPS profiles focused around the Ge3*d*, O1*s*, and N1*s* core levels for Ge surfaces (a) after a dedicated HF-based wet cleaning, (b) after O_2 ICP treatments, and (c) after N_2 ICP oxynitride generation. On the postcleaning sample [Fig. 1(a)], metallic Ge3*d* is detected at a binding energy of 30.1 eV (Ge–Ge bonds). A small and broad peak covering the 32–34 eV range also indicates a mixture of oxidation states.[16] O_2 ICP treatment [Fig. 1(b)] indicates the generation of a major GeO_2 oxide phase ($\Delta E_b \sim 3.5$ eV) with a small GeO ($\Delta E_b \sim 1.2$ eV) contribution. After oxynitridation [Fig. 1(c)], Ge3*d* metallic peak is still detected at 30 eV. A sharp and intense peak is also detected at 32.34 eV ($\Delta E_b = +2.3$ eV) that represents the Ge atoms linked in the oxynitride layer. Peak fitting of the N1*s* spectrum indicated only one peak located at 398.31 eV that corresponds to the N atoms from the oxynitride layer. On the O1*s* spectrum after oxynitridation [Fig. 1(c)], one contribution is extracted that presents a −1 eV chemical shift as compared to the GeO_2 related peak identified on the oxidized surface [Fig. 1(b)]. These observations suggest a quite homogeneous germanium oxynitride layer with a thickness below 6 nm (Ref. 17) (the Ge–Ge metallic peak being detected). Surface layer atomic

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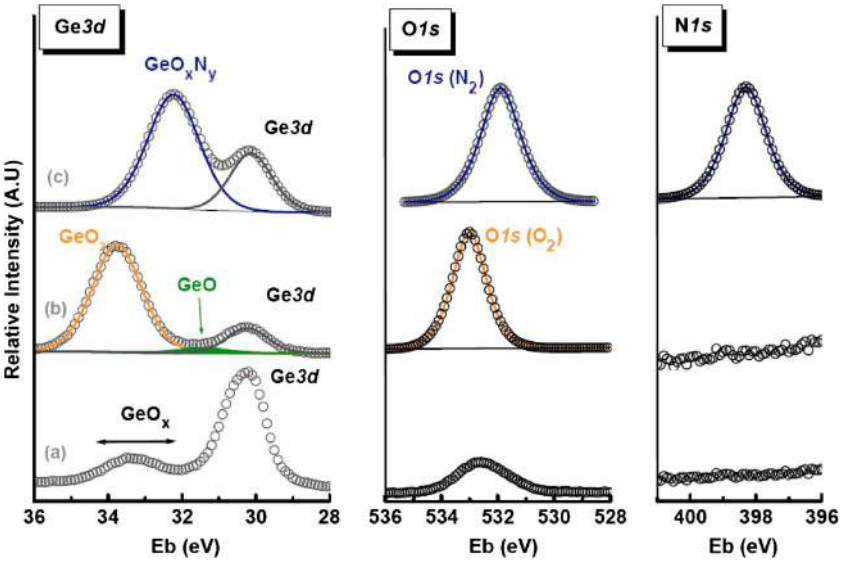

FIG. 1. (Color online) Surface XPS analyses of the binding states around the Ge3*d*, O1s, and N1*s* core level after (a) Ge cleaning,(b) postplasma oxidation with O_2 gas, and (c) post plasma oxynitridation with N_2 gas.

composition is extracted from the XPS measurements and indicates a Ge:O:N composition of 40%:15%:45% close to the 40%:20%:40% of a stoichiometric Ge_2ON_2 layer.

Figure 2(a) is an angle resolved XPS (AR-XPS) profile of the nitrogen/oxygen atomic concentration ratio in the surface layer. Measurements were performed in *ex situ* conditions, after a long time air exposure of the layer. The figure shows a gradual nitrogen profile with concentration increase from surface to volume. Figure 2(b) shows the electron density profile in the layer as measured by x-ray reflectometry (XRR) using a synchrotron radiation at 18 keV energy. Applying a three layer model, a top surface layer is detected with an electron density of 0.8 $Å^{-3}$. Higher electron density of $\rho = 1.15$ $Å^{-3}$, that corresponds to the GeO_xN_y phase, is found underneath. A third deeper and denser region is also extracted with an electron density that increases over $\rho = 1.2$ $Å^{-3}$ that indicates a local enrichment in nitrogen. Total thickness is extracted around 3.5 nm. These results indicate limited oxygen incorporation into the layer that we attribute to a diffusion of ambient H_2O or O_2 species. Spectroscopic ellipsometry measurements yielded a refractive index of 1.7 (at a 632.8 nm wavelength), with an equivalent thickness of 3.1 nm supporting the XRR estimate. AFM measurements also indicate a smooth surface with a rms roughness below 0.2 nm on 1×1 μm^2 scans. All these results demonstrate the high amount of nitrogen incorporated into the quite stoichiometric and very homogeneous 3 nm thick GeO_xN_y layer.

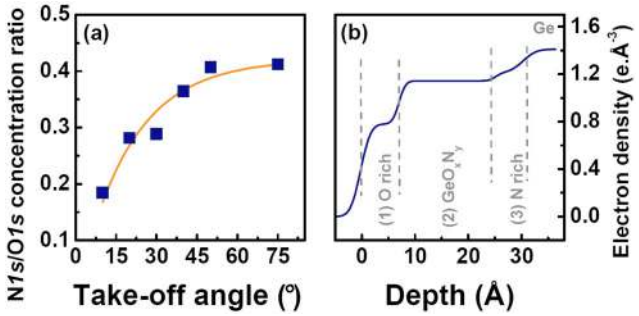

FIG. 2. (Color online) (a) Evolution of the nitrogen/oxygen ratio profiles as a function of the take-off angle (measured with AR-XPS) into the germanium oxynitride layer. (b) Electron density profile extracted from XRR measurements.

Figure 3 is a cross section high-resolution transmission electron microscopy (HR-TEM) observation of the 200 mm GeOI substrates. The 90-nm-thick transferred Ge layer appears defect-free and the thin oxynitride with smooth interfaces is visible. SIMS analysis (inset of Fig. 3) was performed using 2 keV Cs^+ primary ions and ion beam current of 2 nA. Germanium and nitrogen signals present a pronounced peak around the depth of 91 nm confirming their presence in the Ge/BOX interfacial layer. Oxygen is more difficult to quantify because of the presence of the SiO_2 BOX.

Pseudo-MOSFET measurements were finally performed. Electron and hole mobility were extracted following the method developed by Ghibaudo.[18] Figure 4 presents the evolution of the drain current (I_D) as function of the gate voltage (V_G) measured at two different drain voltages $V_D = 200$ mV and $V_D = 1.2$ V. Electron and hole mobility were extracted at

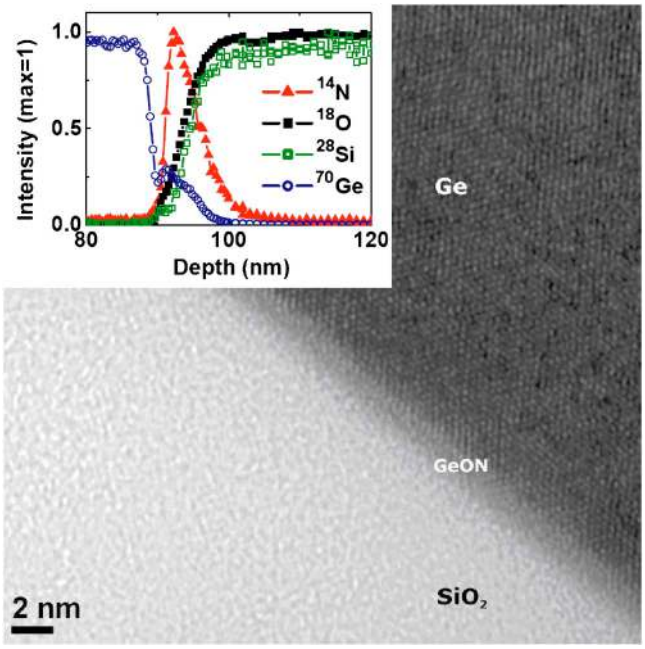

FIG. 3. (Color online) HR-TEM observation of the final GeOI substrates with the oxynitride back interlayer. Corresponding SIMS profiles are also shown in insert.

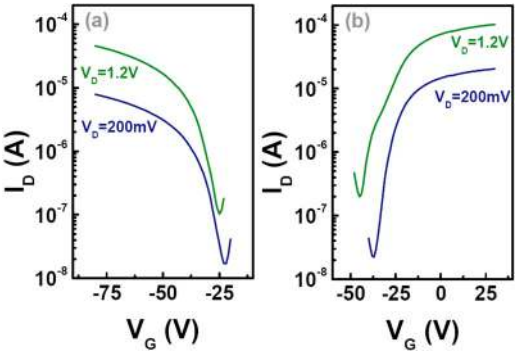

FIG. 4. (Color online) Pseudo-MOSFET drain-current (I_D-V_G) measurements in (a) accumulation and (b) inversion regimes for V_D=200 mV and V_D=1.2 V.

V_D=200 mV. High electronic current is measured and a high electron mobility value μ_e=670 cm^2 V^{-1} s^{-1} is extracted. Hole mobility reaches a much lower maximum value μ_h =100 cm^2 V^{-1} s^{-1}, but mobility attenuation due to the low thickness of the GeOI layer has also to be taken into account in this estimation.[19] Leakage currents through the BOX were found near 50 and 70 pA, respectively preventing a parasitic degradation of the drain current. Density of interface states (D_{it}) was extracted around 6×10^{12} cm^{-2} eV^{-1} that remains high but in the same order as usually observed on Ge MOSFETs. High drain voltage biasing was also studied for V_D =1.2 V. Results confirmed the degradation of the off-state drain current, and an increase of the drain current in both accumulation and inversion. Ratio between pseudo off-state and on-state current is found quite constant for the low/high drain polarization around three decades.

Table I compares electron and hole mobility value that were reported with pseudo-MOSFET measurements on GeOI.[14]We will there refer only to the mobility extracted with pseudo-MOSFET measurements on comparable isolated active layers due to the differences in mobility extractions between pseudo-MOSFET and devices. We previously demonstrated higher hole mobility value (μ_p =300 cm^2 V^{-1} s^{-1}) on GeOI substrates, but very small current was measured in inversion that did not allow to extract electron mobility. Nguyen *et al.*[20] also reported pseudo-MOSFET measurements on GeOI substrates made with the Ge condensation technique. They obtained a record value of μ_h=400 cm^2/V s but also indicated a strong degradation of the inversion mode (no electron mobility extracted). Deguet *et al.*[12] also mentioned and discussed the asymmetric electron and hole mobility degradation on Ge *p*- and *n*-MOSFETs made with GeO_xN_y gate dielectric. An asymmetric density of interface state in the Ge bandgap is believed to be responsible for this phenomenon. There, we confirm that GeO_xN_y layer could achieve an effective passivation that increases the electron mobility, but more complex effects are obtained for the hole mobility. It is believed that the plasma assisted nitrogen incorporation at the Ge/dielectric interface could be responsible, in part, for this reverse tendency that exhibits a strong increase of the electron mobility and degradation of the hole's one.

TABLE I. Comparison of electron and hole mobility extracted from pseudo-MOSFET measurements on GeOI substrates.

Reference	Ge thickness (nm)	μ_h (cm^2 V^{-1} s^{-1})	μ_e (cm^2 V^{-1} s^{-1})
12	100	300	⋯
20	100	400	⋯
21	200	300	350
This work	100	100	670

In conclusion, an innovative GeOI structure was proposed with a 3 nm thick high nitrogen containing (40%) GeO_xN_y interlayer as a back-interface passivation. Based on TEM observations, no defects in the Ge transferred layer, nor any interfacial non homogeneity between the germanium and the oxynitride layer were observed. Electron mobility reaches a maximum value around 670 cm^2 V^{-1} s^{-1} as extracted from pseudo-MOSFET measurements. This is the highest electron mobility value reported on GeOI substrates. It suggests that by controlling the nitrogen incorporation at the Ge-dielectric interface, an efficient passivation can be achieved for electrons. Nevertheless, a strong asymmetry of the passivation is observed and has to be taken into account.

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