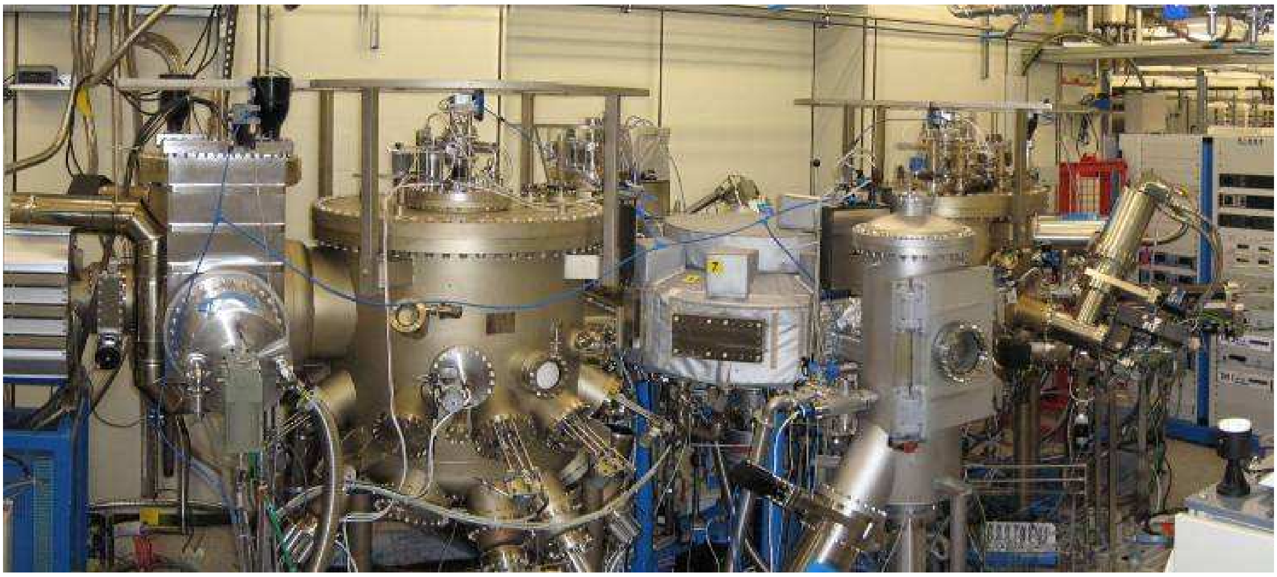

APPLICATION NOTE

State of the art quality of a GeOx interfacial passivation layer formed on Ge(001)

Summary

A number of research efforts have been made to realize Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) on Germanium (Ge) substrates. The choice of Ge as the engineered channel for n-MOS is due to its attractive intrinsic properties (lower effective mass and higher hole mobility of carrier for increasing driving current, and smaller optical bandgap for broader absorption wavelength spectrum). The main challenge to implement high-k dielectrics on Ge-based devices consists in identifying a proper Ge surface passivation method to promote a low density of interfacial states (D_{IT}) and a high channel mobility.

The purpose of this application note is to present such passivation method, using GeOx as an Interfacial Passivation Layer (IPL) between Ge (001) and Al_2O_3 in order to minimize the formation of D_{IT} in the oxide/Ge interface which leads to the Fermi Level Pinning (FLP).

Work was carried out at Riber Si/Ge/III-V Process Technology Center, in Belgium, in collaboration with IMEC team. Growths were carried out in the MBD 49 system.
Thickness uniformity has been controlled by ellipsometry. Structural analyses have been investigated by X-Ray Reflection (XRR). Finally, electrical properties were investigated by I-V and C-V.

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Equipment

Riber/IMEC system is made of two growth reactors connected to a complete automated UHV cluster tool for wafer transfer operations.
Reactors are designed under the same plateform as Riber best seller multi-wafer production system, the MBE 49.
The first reactor, the MBE 49, is dedicated for the growth of III-V semiconductors. Reactor is equipped with standard effusion cells for main materials, Ga, In, Al, model ABN 700, with dopant effusion cells for Si, Be, model ABN 160 and with Valved cracker for Arsenic, model VAC 2000.

The second reactor, the MBD 49, patented by Riber is designed to work under oxygen environment. Reactor is equipped with an Al effusion cell, model ABN 700, a multi-pocket E-gun for Hf, Ti, Ta, Si, La and with an oxygen plasma source.
Riber UHV cluster tool, allows to load/unload and transfer automatically wafers from one chamber to another.
A wafer preparation module is also attached to the cluster tool. This module is equipped with N_2 and H_2 plasma sources and with H_2Se, H_2S, NH_3 and O_2 gas box.

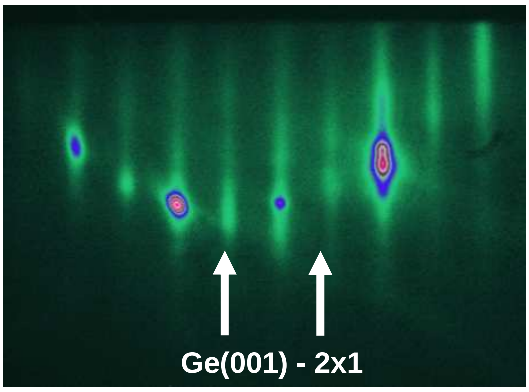

Fig. 1: RHEED pattern of a streak Ge(001) - 2x1, after deoxidation of the native oxide.

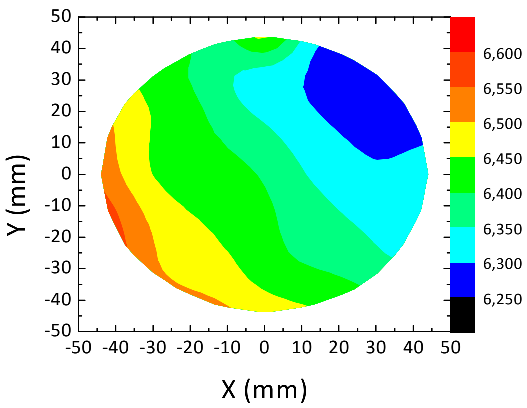

Fig. 2: Ellipsometry mapping of a 5nm Al_2O_3

Structure growth

1- Desorption of native oxide on Ge(001) substrate

Prior to introduction to the MBD reactor, 4-inch n-Ge(001) substrate is chemically treated.
Substrate is then introduced into the preparation module and heated to up to 700℃ to thermally remove in-situ the remaining native oxide, leaving behind a clean reconstructed Ge(001) 2x1 pattern, as shown on figure 1.

2- In-situ GeO_2 formation

Exposure of the Ge surface to an atomic oxygen flux, at a low temperature of about 150℃ results i n the formation of a fully amorphous GeO_2 layer.

3- Al_2O_3 formation

An amorphous layer of 5nm of Al_2O_3 is deposited on top of the GeO_2 by combining Aluminum evaporation with an atomic oxygen flux at a temperature of about 250℃. Ellipsometry mapping, figure 2, shows an excellent thickness uniformity on the whole sample (± 2%).

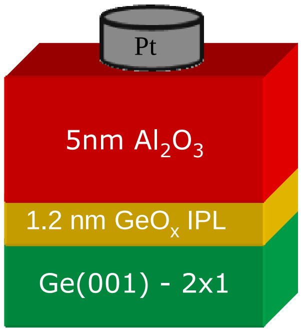

Fig. 3: Formation of a Pt/Al2O3 /GeOx/Ge stack.

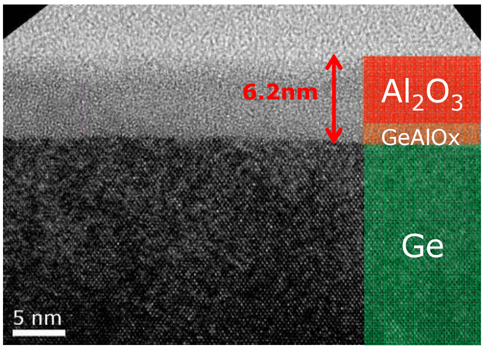

Fig. 4: TEM analysis of a 5nm Al2O3 / 1.2nm GeAlOx/Ge (001) stack.

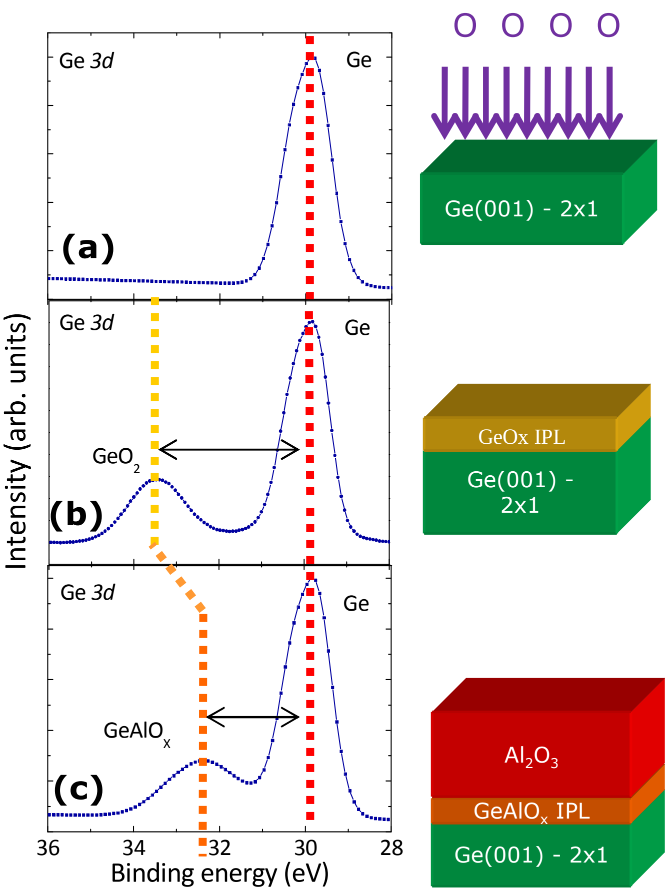

Fig. 5: XPS analysis of the successive growth steps.

4- Pt deposition

Finally, 50nm Pt dots are evaporated ex-situ, through a shadow mask, to make electrical contacts on the capacitor, figure 3.
Capitance-Voltage (C-V) and Current-Voltage (I-V) measurements are performed in a probe station.

To reduce significantly DIT formation and increase electrical properties, several Forming Gas Annealing experiments have been carried out on the stack.

Results

1- Structural properties – TEM analysis

High resolution cross-sectional TEM picture, figure 4, taken along <100>Ge of a stack, demonstrates the good homogeneity of the Al_2O_3 layer and the absence of structural defects like pinholes. Moreover, the Al_2O_3 thin film is completely amorphous with no crystallites in the layer. TEM picture also shows a sharp and uniform interface between GeAlOx and Ge (see step 3 below).

2- Structural properties – XPS analysis

Complete XPS analysis has been processed at each step of the growth process.

Step 1: desorption of the native oxide: spectrum 5a shows no Ge-O peak after deoxidation, result of an oxygen-free clean Ge(001) surface.
This step is performed in the preparation module.

Step 2: In-situ GeO_2 formation: XPS analysis recorded (figure 5b) after 1.2nm thick GeOx layer deposited on Ge substrate results in a binding energy gap of ~ 3.5 eV between Ge and GeOx peak which demonstrates that Ge has been completely oxidized on the required thickness and hence the precise control of all the growth parameters.

Step 3: Deposition of Al_2O_3 on GeOx/Ge: Deposition of 6.2nm of Al_2O_3 leads to a peak energy shifting towards lower energies, figure 5c. Binding energy gap of 2.5 eV is a consequence of an intermixing between GeOx and Al_2O_3 which results in the formation of a GeAlOx layer.

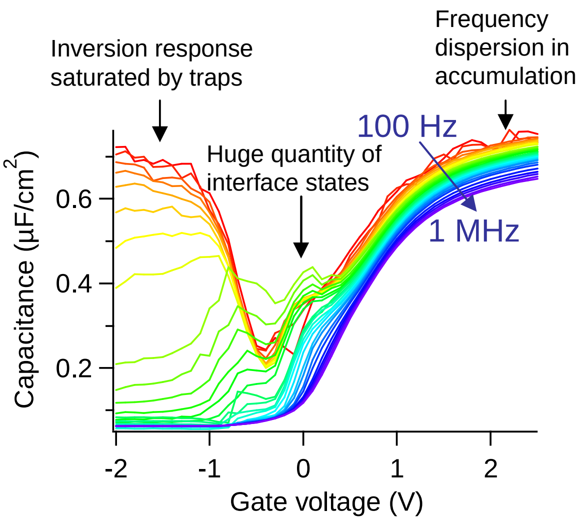

Fig. 6: C-V characteristic of as deposited Pt/9nm Al_2O_3/1.2nm GeOx/ /n-Ge(001) MOS structure.

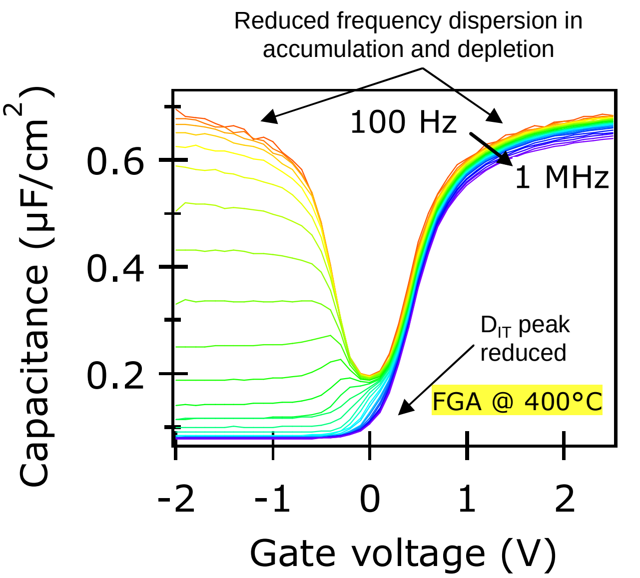

Fig. 7: C-V characteristic of Pt/9nm Al_2O_3/1.2nm GeO_2/ /n-Ge(001) MOS structure, exposed to FGA (10% H2/90%N2 for 5 minutes at 400℃).

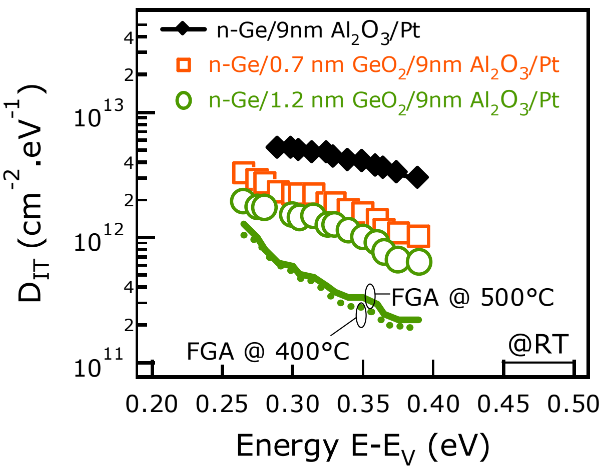

Fig. 8: D_{IT} as a function of the Energy for different MOS structures: Pt/Al_2O_3/n-Ge, Pt/Al_2O_3/GeO_2/n-Ge with and without FGA exposition.

3- Electrical properties – C-V as deposited

Room temperature C-V characterizations of Pt/Al_2O_3/GeO_x/n-Ge(001) MOS structures have been measured at different frequencies (from 100Hz to 1MHz).

The as-deposited C-V curve (figure 6) exhibits high frequency dispersion in accumulation. Moreover, the inversion response seems to be saturated by traps. Finally, the high D_{IT} bumps confirm the presence of huge amount of D_{IT}, leading to the Fermi Level Pinning.

4- Electrical properties – C-V after FGA

The same electrical study has been carried out on MOS structures exposed to FGA (10% H_2 / 90% N_2 for 5 min at 400℃).

C-V curves show tremendous improvements as shown on figure 7. Indeed frequency dispersion in accumulation and depletion are much lower than previously (figure 6) without FGA.

D_{IT} bumps has been drastically reduced.

5- Electrical properties - extraction of D_{IT}

MOS structures with different GeOx IPL thickness (0.7nm and 1.2nm) have been grown and compared, in order to demonstrate the impact on the amount of D_{IT}.

Figure 8, representing D_{IT} formation function of the energy , clearly shows the necessity of the GeO_2 IPL layer to decrease the presence of D_{IT}

MOS structure were then exposed to FGA under the same conditions but at two temperatures, 400℃ and 500℃, for 5 minutes. Again, figure 8 shows the importance of the annealing step. D_{IT} is drastically reduced after FGA and electrical properties are radically improved. Optimal conditions were reached at 400℃.

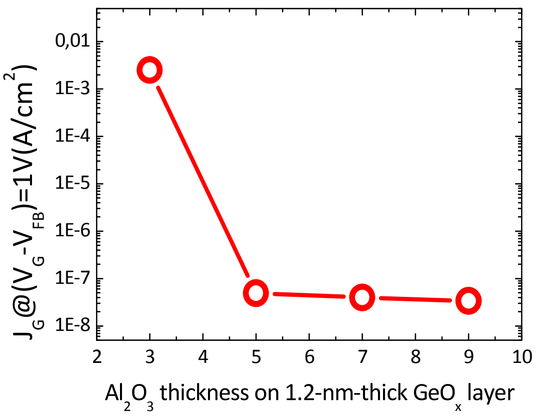

Fig. 9: Leakage current as a function of Al2O3 thickness on 1.2nm thick GeO2/Ge (001).

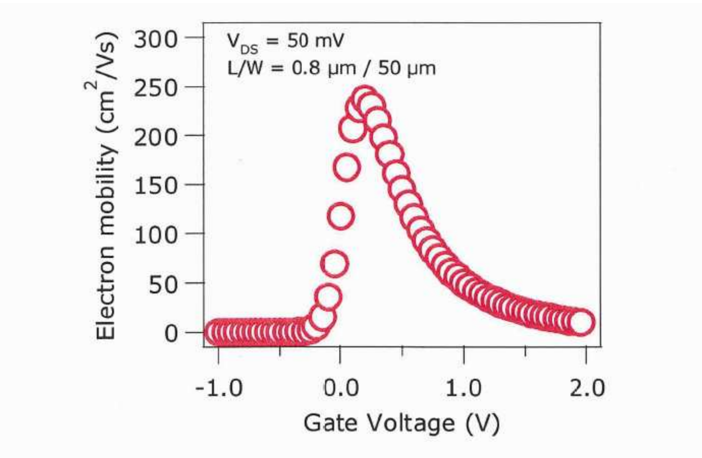

Fig. 10: Electron mobility as a function of the gate voltage for transistor structures based on Pt/Al2O3/GeO2/n-Ge

6- Electrical properties – Leakage current

Figure 9 shows the impact of the Al_2O_3 thickness on the leakage current density of the Pt/Al_2O_3/GeO_2/Ge MOS structure. Below 5nm, Al_2O_3 becomes leaky.

7- Electron mobility of transistor

Figure 10 shows the electron mobility of a transistor based on such passivation stack.
World record mobility 250cm²/Vs is obtained.

Conclusion

This work investigated Al_2O_3/GeO_2/Ge materials combination using molecular beam deposition technique.
Results demonstrated that the fully automated Riber MBD 49-200mm deposition system, equipped with market leading effusion sources and latest technical accessories, provides an excellent control of the growth parameters, reproducible growth to growth conditions, delivering state of the art results.
Besides, we demonstrated that in-situ controlled GeO_2 growth between Ge substrate and Al_2O_3 dielectric provides an efficient passivation of Pt/Al_2O_3/GeO_2/Ge stacks, significantly decreasing D_{IT} .

About PTC

Riber PTC in collaboration with IMEC, Belgium, allows customers and prospective users to test the MBD 49-200mm for growth of structures or target specific device properties to enhance and accelerate their process knowledge. Training courses may be tailored to meet individual requirements. Experience accumulated in advance of system delivery saves month process development.