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Molecular beam epitaxy passivation studies of Ge and III–V semiconductors for advanced CMOS

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ABSTRACT

Future CMOS technologies will require the use of substrate material with a very high mobility in order to fulfil the performance requirements. Therefore, combination of Ge p-MOS with n-MOS devices made out of high mobility III/V compounds, such as GaAs, has recently received some attention for its possible use in advanced CMOS applications. In this work, the physical, chemical and electrical properties of Al_2O_3 high-κ oxide deposited on Ge and GaAs, using Molecular Beam Deposition (MBD) technique, have been investigated.

1. Introduction

Future improvements in MOSFETs performances will require high mobility (high-μ) semiconductor channels. The integration of novel materials with higher carrier mobility, to increase drive current capability, is a real challenge to overcome silicon-based CMOS. One solution is to use a germanium-based channel for pMOS combined with a III–V-based channel for nMOS. The availability of III–V for CMOS applications is also opening the opportunity to co-integrate optoelectronic and electronic devices on the same platform.

The main issues of such devices consist in obtaining low leakage current, low interface state density and high carrier mobility in the channel [1,2]. Therefore, passivation of the interface between gate oxide and Ge/III–V materials will require innovations to reach high device performances and EOT scaling in agreement with ITRS roadmap expectations. For this reason, a great technological effort is required to produce systems that yield the desired quality in terms of material purity, uniformity and interface control. Molecular Beam Deposition (MBD) has been shown to be an attractive technique to fabricate such devices, due to its potential to control the *in situ* deposition and also the interface between high-κ oxides and high-μ substrates at an atomic scale [3–5]. In this work we investigate the passivation of n-Ge(001) – using GeO_2 as an interfacial passivation layer (IPL) – and p-GaAs(001) by engineering the deposition of the high-κ dielectric. Al_2O_3, with its moderate κ-value of 10 and its large band offset discontinuities (>2 eV), is therefore a good candidate to be used as high-κ oxide [6,7].

2. Experimental setup

Experiments were carried out using a Riber 200 mm molecular beam epitaxy cluster production system. This unique multi chamber MBE system is composed of a MBE49 III–V growth reactor (with a valved cracker cell of As, four double filament effusion cells: Ga, Al, In, Ge and two doping cells: Si, Be); a MBD49 high-κ oxide reactor (with two double filament effusion cells: Al, Ga and Si, Ge, La, Al_2O_3 and $Ga_3Gd_5O_{12}$ pure targets divided in two electron beam evaporation guns, completed by two plasma sources: O_2 and N_2), a passivation unit (for sample degassing and for chalcogenide – S & Se passivation studies) and a 25 holders capacitance loading chamber. All these three chambers are equipped with Reflective High Energy Electron Diffraction (RHEED) analysis system. The key advantage of this system is that each chamber is connected with one robotics and is under UHV with a base pressure of 10^{-11} Torr. The high flexibility of current experimental setups enables us to perform various interfacial engineering schemes.

3. Ge-based surfaces passivation

In a first part, the passivation of germanium will be discussed. It is well known that the direct deposition of Al_2O_3 oxide on Ge(001)

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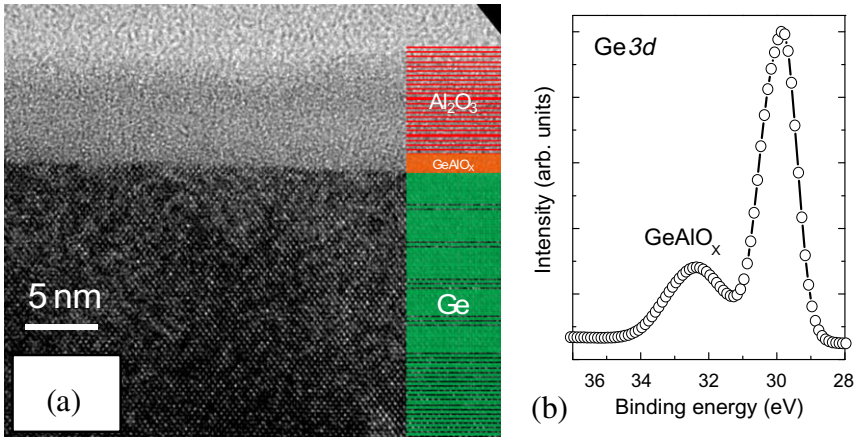

Fig. 1. (a) TEM picture of a n-Ge(001)/GeO_2/Al_2O_3 heterostructure showing a very sharp interface. (b) XPS Ge *3d* spectra of the n-Ge/GeO_2/Al_2O_3 heterostructure.

does not provide a good passivation of the substrate [8,9]. Indeed, Al_2O_3 straight on Ge leads to the formation of an undesirable interfacial layer which presents a very high interface state density ($D_{it} \sim 5 \times 10^{12}$ $cm^{-2}.eV^{-1}$). In this case, an IPL is necessary in order to avoid any unstable layer formation, leading to the presence of traps at the Ge/high-κ interface. One solution proposed in this work is to form an *in situ* controlled GeO_2 interlayer between Ge and the high-κ layer, to improve Ge passivation [6,9,10].

Prior to MBD, n-type Ge(001) wafers were chemically treated with $NH_4OH/H_2O_2/H_2O$ followed by 2% HF dip. The Ge native oxide was then thermally *in situ* desorbed by heating the substrate up to 700 °C for 30 min until a (2×1) reconstruction was observed by Reflective High Energy Electron Diffraction (RHEED), indicative of an oxide free Ge(001) surface. The GeO_2 interfacial layer was formed by exposing the clean Ge(001)-2×1 surface to an atomic oxygen flux at a low temperature of $T \sim 150$ °C. The Al_2O_3 thin films were elaborated by co-deposition of aluminum evaporated from a double filament Knudsen cell with an atomic oxygen flux of $P(O_{ato}) \sim 3.10^{-6}$ Torr from an Oxford plasma source. During the deposition, the substrate temperature was around $T_D = 250$ °C in order to obtain an amorphous layer. Finally, to form MOS capacitors, a top electrode, consisting in a 50-nm-thick Pt layer, was deposited *ex situ* on the stack through a shadow mask to define circular dots of 6.36×10^{-5} cm^2 area. Then, the samples are exposed to a Forming Gas Anneal in 10% H_2/90% N_2 for 5 min.

In order to study the structural quality of the n-Ge(001)/GeO_2/Al_2O_3 gate stack, a High Resolution Cross-Sectional Transmission Electron Microscopy (HR-TEM) image taken along $\langle 110 \rangle_{Ge}$ of a stack with a 8.5 nm Al_2O_3 layer is shown in Fig. 1a. The TEM picture evidences the good homogeneity of the stack and the absence of structural defects (like pinholes, etch, etc.) on the Ge surface which could occur during the first step of the oxide deposition. The Al_2O_3 thin film presents a uniform thickness of 8 ± 0.5 nm and a relatively flat surface. The Al_2O_3 thin film is completely amorphous and does not present any crystallites in the layer. The Ge/GeO_2–Al_2O_3 interface is sharp at the atomic-scale and continuous. The HR-TEM does not clearly exhibit the presence of the thin interfacial layer. X-ray Photoelectrons Spectroscopy (XPS) analysis is required to determine the chemistry at the interface.

The Ge *3d* XPS spectra of a n-Ge(001)/GeO_2/Al_2O_3 heterostructure, is presented in Fig. 1b. The exposure of the Ge surface to an oxygen plasma leads to the formation of a GeO_2 completely oxidized ($\Delta BE_{(Ge-GeO2)} \sim 3.5$ eV). But after the deposition of the Al_2O_3 oxide on the Ge(001)/GeO_2 heterostructure, a shift of the Ge-O peak to the lower energy ($\Delta BE_{(Ge-GeOx)} \sim 2.5$ eV) reveals an impact of the high-κ deposition on GeO_2 layer. This behaviour suggests the change of the GeO_2 interfacial layer into germanium suboxides, GeO_x, or to the formation of aluminium germanate ($GeAlO_X$) at the high-κ/GeO_2 interface.

Fig. 2 presents the *C–V* characteristic of n-Ge/1.2-nm-GeO_2/9-nm-Al_2O_3/Pt stacks, measured from inversion to accumulation and taken at different frequencies (100 Hz–1 MHz). The capacitors were exposed to a FGA anneal at 400 °C during 5 min. A well-be-

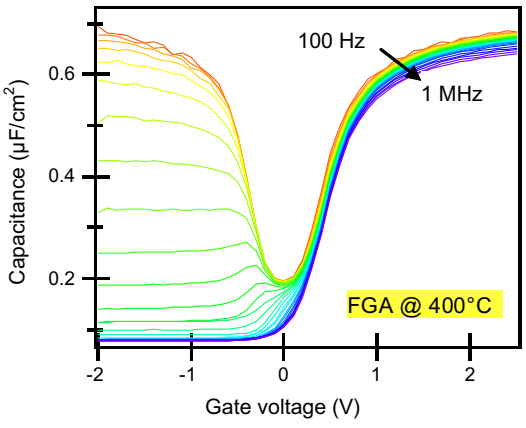

Fig. 2. *C–V* characterization of n-Ge(001)/GeO_2/Al_2O_3 gate stack after FGA taken at different frequencies.

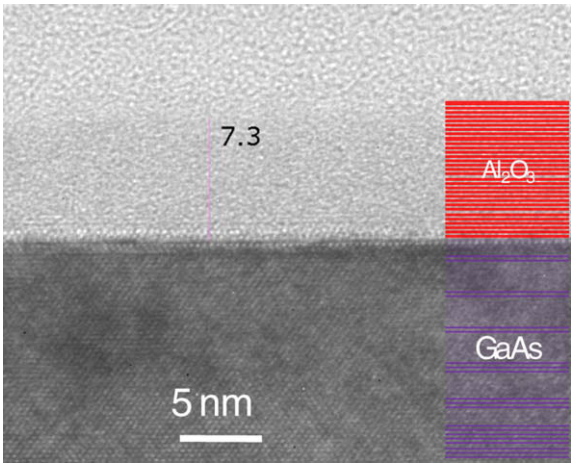

Fig. 3. TEM picture of a p-GaAs(001)/Al_2O_3 heterostructure showing a very sharp interface.