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Use of high order precursors for manufacturing gate all around devices

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ABSTRACT

Epitaxial growth of strained and defect free SiGe layers grown with disilane and digermane was investigated. This precursors set allows to cover a broad range of Ge concentration (15–65%) at low temperatures (400–550 °C). It was shown that change of carrier gas (from H_2 to N_2) does not increase SiGe growth rate but significantly reduces Ge concentration. Increase of total process pressure considerably reduces SiGe growth rate which is attributed to peculiarities of digermane decomposition and influence of hydrogen surface passivation on disilane decomposition. It was shown that both disilane and digermane can be successfully combined with conventional precursors like silane and germane. These experiments suggested that digermane decomposition is the main driver of the growth rate increase during SiGe growth. Based on the presented data we demonstrated growth of different SiGe/Si and SiGe/Ge stacks with high quality necessary for production of gate all around field effect transistors.

1. Introduction

Horizontal nanowire or gate all around (GAA) Field Effect Transistors (FETs) are being considered a next logical step in scaling of Fin FETs for the 7 and 5 nm technological nodes (Fig. 1) [1–3]. Their production promises little deviation from a standard Fin FETs processing flow and dramatic improvement of electro-static properties. In order to produce GAA FETs a stacking of two materials, typically Si and SiGe, is used. Depending on the need, any of these materials can serve as either active or sacrificial layer. In the case of Si/SiGe GAA stack, typically SiGe with Ge content (~25–30%) is used. It is very well known that such configuration can be easily grown with sharp interfaces between layers. The epi growth is typically done at the temperatures around 600 °C with decent growth rates (GR) for both materials. Further, the sacrificial layer can be removed either by wet or dry selective etching.

An ultimate scaling of this technology assumes use of either Si or Ge and SiGe with high Ge content close to 50–70%. Growth of such stacks (Si/SiGe or Ge/SiGe) is challenging since it can only be done at low temperatures in order to keep the structure strained. In our case typical temperatures for $Si_{0.5}Ge_{0.5}$ growth are in the range of 500 °C whereas strained Ge is grown on SiGe strain relaxed buffer (SRB) at 350 °C. Conventional precursors (SiH_4, DCS, GeH_4) either offer an extremely low growth rate at such temperatures or no growth at all.

This motivated us to look at high order precursors which potentially offer reasonable GR of Si, SiGe and Ge at mentioned above temperatures [4].

In this contribution we first discuss SiGe growth with disilane and degermine since it is the main building block of a GAA structure. We will present growth characteristics, influence of carrier gas, total pressure, etc. Finally we will discuss application of disilane/digermane set of precursors for growth of Si/SiGe and Ge/SiGe stacks.

2. Experimental details

All layers were deposited on blanket 300 mm (100) Si wafers using an ASM Epsilon™ 3200 and Intrepid XP™ epi tools, which are horizontal cold wall, load-locked reduced pressure chemical vapor deposition systems designed for production applications.

In order to ensure the epitaxial growth of the SiGe/Si and SiGe/Ge epi stacks the native oxide formed on the Si and SiGe surface must be removed. In the case of blanket Si wafers a bake in H_2 at 1050 °C was used. A short dip in diluted HF combined with a H_2 bake at 800 °C at pressure of 20 Torr was used in the case of epi stacks growth on SiGe strain relaxed buffers in order to minimize surface roughening.

For the deposition of $Si_{1-x}Ge_x$ layers different combinations of Ge and Si containing precursors were used: dichlorosilane (SiH_2Cl_2) (DCS), silane (SiH_4) and disilane (Si_2H_6) as Si precursors; germane (GeH_4) and digermane (Ge_2H_6) as Ge precursors.

H_2 or N_2 was used as the carrier gas with the flow kept at few tens of slm. All experiments were done at a reduced pressure of 20 Torr except stated otherwise. The temperature of the growth was kept in the range

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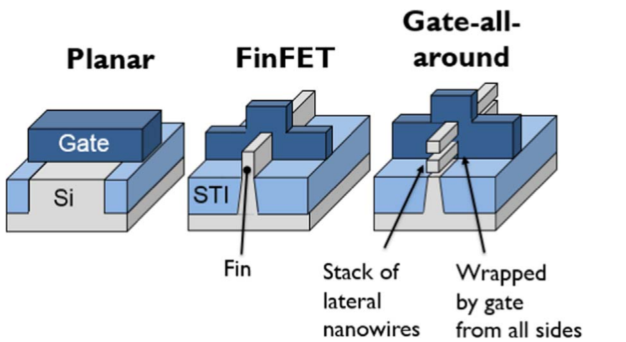

Fig. 1. Scaling scenario from planar to FinFET to GAA devices. Vertical stacking increases the active volume which enables an increase of the drive current. Gate all around offers optimal electrostatic control.

of 400–550 °C, SiGe/Ge stack was grown at 350 °C. The growth temperature for different processes was chosen such that SiGe or Ge layers were kept strained.

High resolution X-ray diffraction (HRXRD) and X-ray reflection (XRR) (JVX7300LM X-ray metrology) were used for estimation of the Ge concentration and layer thickness of the SiGe/Si and Ge/SiGe stacks.

Finally, transmission electron microscopy (TEM) and high angle annular dark field scanning transmission electron microscopy (HAADF-STEM) were used to evaluate SiGe/Si and SiGe/Ge stacks. Specimen preparation for the TEM studies was performed with a dual beam - focused ion beam (FIB)/SEM (Helios 450HP) equipped with an Easylift needle to perform in-situ lift-out of the region of interest from the sample which was studied in Tecnai 30 F microscope operating at 300 kV. The investigated sample thickness was ~ 100 nm.

In order to verify Ge content obtained by HRXRD, energy-dispersive X-ray spectroscopy (EDS) was performed with superX detector system attached to the FEI Titan 60–300: 4 Silicon-drift detectors (SDDs) with 0.9sr solid angle.

3. SiGe growth with disilane and digermane

As was mentioned previously, the main motivation for high order precursors investigation is a possibility to grow epi layers of Si, SiGe and Ge at temperatures not accessible for conventional precursors. Fig. 2 shows that high orders precursors like disilane, trisilane and digermane allow either to decrease growth temperature or increase growth rate at particular temperature compared to conventional

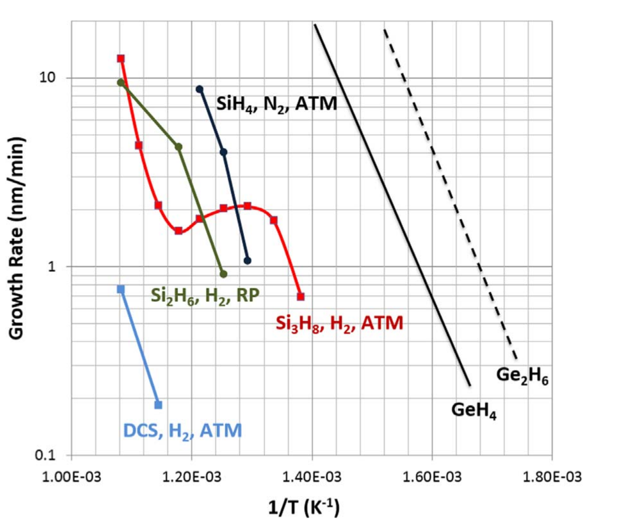

Fig. 2. Arrhenius plots for different precursors. Most of data for Si precursors are obtained at atmospheric pressure, whereas for Ge precursors at low pressure. Arrhenius plot for GeH_4 is adapted from [5], for Ge_2H_6 from [6].

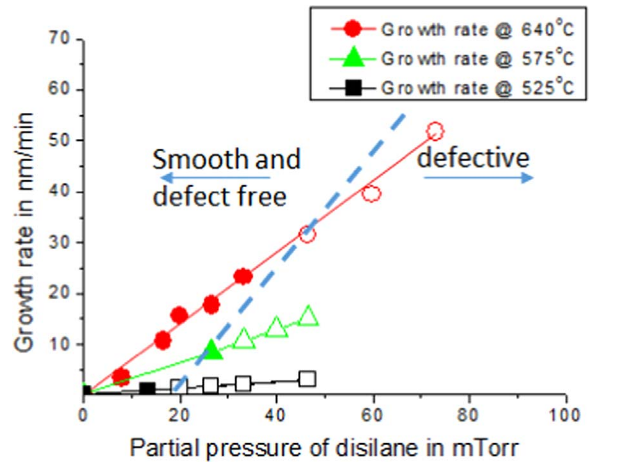

Fig. 3. Dependence of Si growth rate as function of disilane partial pressure. Note the critical partial pressures of digermane for deposition of defect free epitaxial Si layers at different temperatures. Layers roughness was investigated by differential interference contrast microscopy. Adapted from [9].

precursors (SiH_4, DCS, GeH_4). It must be mentioned that growth rates depend very much on various growth parameters (like precursors flows, carrier gas and its flow, pressure, etc.) and use of a particular precursor is dictated by application. If we look for example at Fig. 3, which shows Si growth rate using disilane as function of disilane partial pressure (flow), it is clear that rather narrow range of usable disilane flows is accessible. When disilane flow becomes too high at the particular temperature, Si epitaxial growth brakes down and polycrystalline material is deposited due to limited surface mobility of reacting species. Such behavior is usual and can be experienced with practically all precursors. Combining disilane with germane or digermane changes the critical disilane flow and much higher disilane flows can be used. This can be explained by presence of Ge containing precursor which usually acts as catalyzer and allows to grow SiGe with much higher growth rates and lower temperatures compared to Si growth [7].

Combination of disilane and digermane allows to grow SiGe in a wide range of temperatures (400–550 °C) and wide range of Ge concentration: in our case from 15% up to 65%. It should be noted that eventually pure Ge can be grown using digermane only at temperatures as low as 275 °C as was shown in [6]. Typical dependencies of Ge concentration in SiGe layers grown at different temperatures as function of digermane flow at constant disilane flow are presented in Fig. 4. Two effects are well presented: increase of digermane flow and decrease of process temperature cause increase of Ge concentration in the final layer.

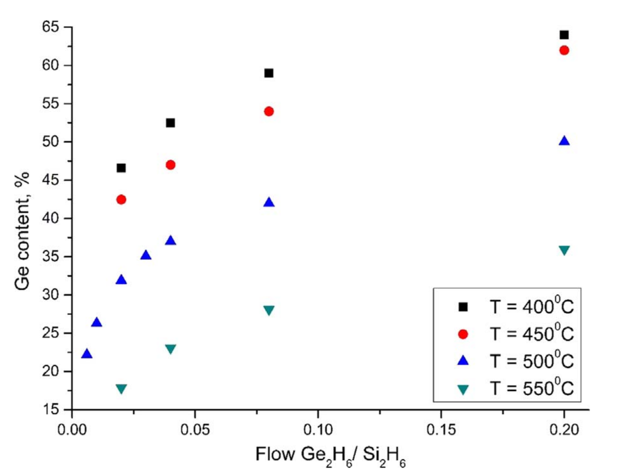

Fig. 4. Dependence of Ge concentration in SiGe layers on digermane flow (0–1000 sccm) at constant disilane flow (50 sccm).