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HIGH Ge CONTENT Si / SiGe HETEROSTRUCTURES FOR MICROELECTRONICS AND OPTOELECTRONICS PURPOSES

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We have studied the growth by Reduced Pressure Chemical Vapor Deposition of (i) high Ge econtent (from 20% up to 55%) SiGe virtual substrates (ii) thick, pure Ge layers and (iii) Ge islands / Si stacks on Si(001), focusing on their surface and film morphologies. (i) Such SiGe virtual substrates can be used as starting materials for the formation of SiGe On Insulator or tensile-strained Silicon On Insulator substrates. In a bulk form, they can serve as templates for the growth of tensile-strained Si surface channels with both high electron and hole mobilities (for Ge contents > 30%). We have first extracted the macroscopic degree of strain relaxation (R ~ 96 ± 1.5%) and the Ge concentration inside our virtual substrates from X-ray diffraction measurements. The misfit dislocations introduced to plastically relax the lattice mismatch between Si and SiGe are mostly confined in the graded layer (~ 10% Ge / µm grade), as confirmed by cross-sectional transmission electron microscopy (see Fig. 1). The threading dislocations density obtained for Ge concentrations of 20% and 27% is indeed typically of the order of 7.5E5 cm^{-2}. The surface root mean square roughness increase when the Ge content exceeds 30% is not that important : the rms is indeed only of 4 to 5 nm for Ge concentrations in-between 30% and 55% (vs 2 to 3 nm for 20% and 27%). The spatial wavelength of the cross-hatch undulations is in-between 1 and 2 µm, this whatever the Ge content. A chemical mechanical polishing step in conjunction with a “HF-last” wet cleaning and H_2 bake (2 min., T ≥ 800°C) can however make the surface fit for some epitaxial SiGe re-growth, with a smooth resulting morphology. We have grown a MODFET-like heterostructures in order to assess the electronic quality of our RP-CVD grown SiGe virtual substrates. A well-behaved 2-dimensional electron gas in the Si channel has been obtained, with electron sheet densities and mobilities at 1.45K of 5.4E11 cm^{-2} and 212 000 $cm^2V^{-1}s^{-1}$, respectively (see Fig. 1). (ii) As far as pure Ge on Si(001) is concerned, we have first of all studied the growth kinetics of Ge (using GeH_4). At low temperatures (400°C - 550°C), the Ge growth rate increases overtime, which is most probably due to a facetted surface. At higher temperatures (≥ 600°C), the Ge growth rate is constant overtime (smoother surface). The low activation energy E_a = 6.9 kcal. $mol.^{-1}$ which is associated to the growth rate increase with the temperature implies that we in a supply-limited regime. We have also studied the structural and optical properties of thick Ge layers grown using a low temperature (400°C) / high temperature (600-850°C) approach (see Fig. 2). A tensile strain configuration (R ~ 103%) has been clearly evidenced for those Ge films, which are rather smooth (rms roughness : ~ 2 nm). This tensile strain is most probably linked to linear coefficients of thermal expansion which are larger for Ge than for Si. A CMP step in conjunction with the appropriate wet cleaning and H_2 bake (2 min., T > 700°C) can make the surface fit for some epitaxial Ge re-growth, with a

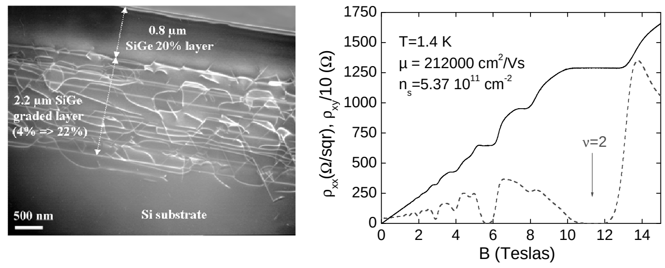
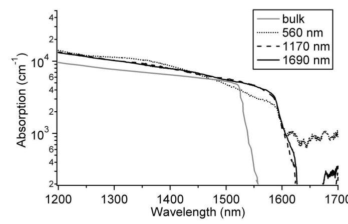
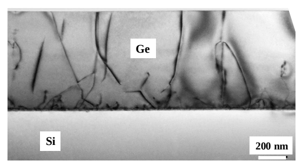


Fig. 1 : (left) cross-sectional TEM image of a typical SiGe virtual substrate; (right) 2DEG longitudinal resistivity (dotted line) and Hall resistivity (full curve) for a 10 nm tensile–strained Si channel embedded inside SiGe 26%.

smooth resulting morphology (rms : ~ 0.5 nm). The Ge layers produced, which have a threading dislocation density of ~ 3E7 cm^{-2}, are of high optical quality. Absorption coefficients equal to 10000 cm^{-1} @ 1.3 µm and 4500 cm^{-1} @ 1.55 µm have indeed been found in our samples. A 30 meV bandgap shrinkage with respect to bulk Ge (0.77 eV ⇔ 0.80 eV) is observed as well in those tensile-strained Ge epilayers (see Fig. 2). Such Ge epilayers should be handy for the production of Ge-On-Insulator substrates or (when selectively grown on patterned optical substrates) for infra-red photo-detectors.





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(iii) Finally, the aim being to obtain Ge quantum dots multilayers capable of detecting light @ 1.55 µm (for photo-detection and modulation purposes), we have first of all highlighted the relationships existing between the process conditions (i.e. growth temperature and pressure, germane flow, amount of Ge deposited etc) and the morphology of the Ge islands on Si(001) in terms of density, shape and dimensions. We have then conducted an optimization in low temperature photo-luminescence on single layers of Ge QDs capped with Si in order to obtain well-controlled QDs emitting light at wavelengths superior or equal to 1.55 µm. This being done, we have stacked those Ge QDs layers one upon the other (with Si spacers in-between) and studied their structural properties and optical responses, with promising preliminary results (see Fig. 3).

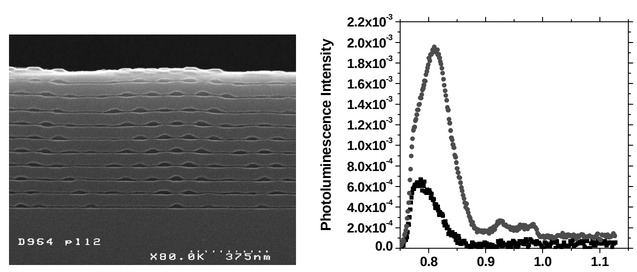

Figure 3 : (left) cross-sectional SEM image of a 10 periods (Ge QDs / Si 75 nm spacer} stack. (right) 10K PL spectra of either one (black) or 10 (red) Ge QDs layers, highlighting the increase of the integrated signal @ 1.55 µm (associated to Ge QDs) with the number of layers.