

## MEB growth of tensile-strained Ge/Si(001)

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Germanium is an indirect bandgap semiconductor but it has been recently demonstrated that strong optical gain could be obtained in tensile-strained and *n*-doped Ge layers. Laser emission has been obtained under optical pumping at room temperature using Ge as the active layer [1]. Application of a tensile strain in Ge allows to lower the energy difference between the indirect L valley and the  $\Gamma$  zone center valley. The tensile strain also lifts the degeneracy between heavy hole and light hole valence bands [2]. On the other hand, *n*-type doping of Ge leads to a more efficient population of the zone center  $\Gamma$  valley and thus enhances optical recombination at Brillouin zone center [3, 4].

Tensile-strained Ge can be obtained via several approaches: use the difference of thermal expansion coefficients between Ge and Si during Ge/Si growth followed by thermal annealing or Ge growth on a larger lattice-parameter substrate such as InGaAs or GeSn buffer layers. In the case of Ge/Si growth, it is important to control the crystalline quality of Ge, since a lattice mismatch of 4.1% between Ge and Si generates significant density of dislocations, which act as non-radiative recombination centers.

We report here the Ge growth on Si(001) substrates using molecular-beam epitaxy (MBE). Compared to Chemical-Vapor Deposition (CVD) growth, one of the advantages of the MBE technique is that it does not need high temperature growth to dissociate gas precursors, allowing thus to control the density of threading dislocations and the surface roughness of the Ge epilayers. We have shown, for example, that there exists an extreme narrow window of temperature of 250-300 °C where the Stranski-Krastanov growth of Ge on Si can be suppressed and a two-dimensional growth can be obtained from the first layer up to a thickness larger than 200 nm (Fig. 1). The resulting Ge epilayers are almost free of threading dislocations. We have also investigated the effect of different parameters on the strain state of Ge epilayers such as annealing conditions, film thickness and growth temperature. An average tensile strain of 0.2 – 0.25 is obtained in Ge epilayers. In particular, we show that the growth temperature is one of the most critical parameters that needs to be controlled. For a growth temperature higher than 700 °C, Si from the substrate diffuses upwards to the Ge layers, resulting in the formation of a SiGe alloy. Finally, we propose to use a multilayer of carbon near the Si/Ge interface to suppress Si/Ge interdiffusion.

[1] J. Liu *et al.*, Opt. Lett. **35**, 679 (2010).

[2] J. Liu *et al.*, Opt. Express **15**, 11272 (2007).

[3] X. Sun *et al.*, Appl. Phys. Lett. **95**, 011911 (2009).

[4] El Kurdi *et al.*, Appl. Phys. Lett. **94**, 191107 (2009).

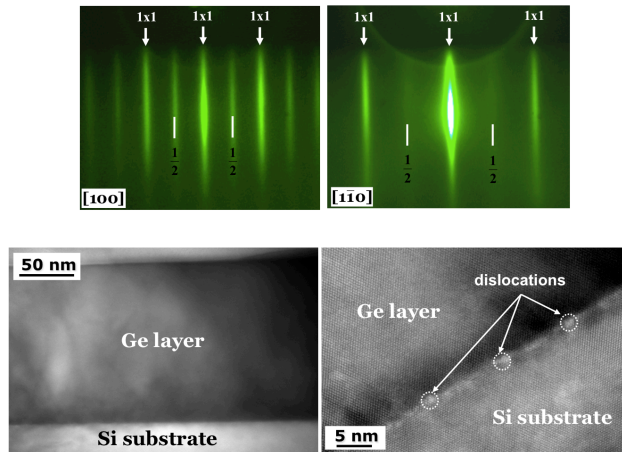


Fig. 1: (upper): RHEED patterns taken along [100] and [1-10] azimuths observed during the growth of the first Ge layer on Si at a temperature of 300 °C. The islanding formation is completely suppressed and a two-dimensional growth is observed up to a thickness larger than 200 nm; (lower) Cross-sectional TEM images of a 150 nm thick Ge layer grown on Si at 300 °C, some interface dislocations are observed but threading dislocations are almost absent.

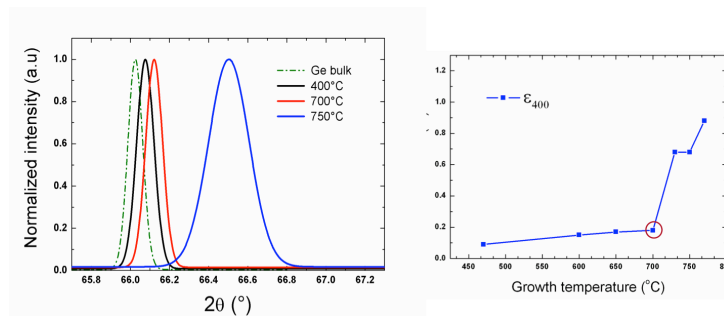


Fig. 2: Evolution of XRD curves (left) and of the (400) peak position of a 300 nm thick Ge layer as a function of the growth temperature (right). The (400) peak is found to be shifted towards larger diffraction angles than that for a bulk Ge, indicating a reduction of out-of-plane lattice constant, i.e., an increase of in-plane lattice constant due to the biaxial tensile stress.

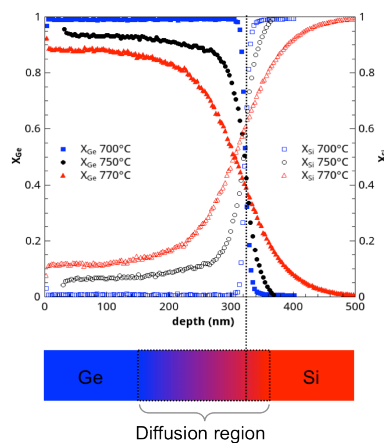


Fig. 3: SIMS depth profiles of Ge and Si of a 300 nm thick Ge layer grown on Si at three substrate temperatures: 700, 750 and 770 °C (upper). The diffusion of Si upwards the Ge layer becomes remarkable at 750 °C while almost no Si is found in the Ge layer at 700 °C. Schema (lower) illustrating the existence of an asymmetric region of Ge/Si interdiffusion near the interface due to a higher diffusion coefficient of Si into Ge compared to that of Ge to Si.