Growth and exploitation of strained Ge/(Si)GeSn heterostructures for optical, electrical and thermoelectric applications

S. Wirths[1], S. Stefanov[2], J.-H Fournier-Lupien[5], Z. Ikonic[3], S. Chiussi[2], O. Moutanabbir[5], A.T. Tiedemann[1], P. Bernardy[1], B. Holländer[1], G. Mussler[1], T. Stoica[1], J.M. Hartmann[4], D. Grützmacher[1], S. Mantl[1], D. Buca[1*]

[1]Peter Grünberg Institute 9 and JARA - FIT, Forschungszentrum Juelich, 52425 Juelich, Germany

[2]Dpto. Física Aplicada, Univ. de Vigo, Rua Maxwell s/n, Campus Universitario, 36310 Vigo, Spain

[3]Institute of Microwaves and Photonics, University of Leeds, LS2 9JT, United Kingdom

[4]CEA, LETI, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble, France

[5]Dept. of Engineering Physics, Ecole Polytechnique de Montreal, Montreal, H3T 1J4, Canada

*Tel: +49-2461-61-3663, Fax: +49-2461-61-4673, E-mail: d.m.buca@fz-juelich.de

1. Introduction

It is now beyond controversy that one of the major issues of future information processing systems is power consumption. Referring to this optical interconnects will play a key role, since electrical interconnects consume over 50% of microprocessor power [1]. Hence, the integration of Si based photonics and CMOS electronics on a common platform is considered to be the Holy Grail.

Recently, binary GeSn alloys attracted lots of research interest due to their “directness” given by the low energy difference between the Γ and L valleys offering new possibilities of strain engineering [2]. Moreover, possessing low band-gaps and low effective charge carriers masses as compared to Si(Ge) these alloys will enable novel nanoelectronic developments. The small band-gap strongly increases the tunneling probability and thus the on-currents in Tunnel-FETs, a novel class of ultra low power devices like Tunnel-FETs [3, 4].

Additionally, the development of Si-Ge-Sn ternary alloys and heterostructures will also create valuable opportunities to achieve an efficient phonon engineering to control lattice thermal conductivity. This capability can be greatly enhanced through precise nanostructuring of these systems with potential impact on thermoelectric applications.

2. Experimental

Several groups succeeded in synthesizing (Si)GeSn alloys applying different growth techniques like APCVD [5], UHVCVD [6], MBE [7] or PLIE [8]. Our approach is based upon Reduced Pressure CVD [9] with showerhead technology using $SnCl_4$, Ge_2H_6 and Si_2H_6 precursors appropriate for growth temperatures between 350°C and 475°C. Our research is focused on strain-engineering of (Si)GeSn alloys and tensile strained Ge in order to achieve direct band-gap group IV semiconductors and demonstrate proof of concepts for optoelectronic, electronic, and nano-thermoelectric devices.

3. Results and discussion

Theoretical electronic band calculations show that GeSn binaries as well as tensile strained Ge become direct band-gap semiconductors if grown on a buffer with a lattice constant of about 5.75 Å. Fig. 1 depicts the calculated band-structure of a QW sGe/SiGeSn heterostructure suitable for lasing using a highly tensile strained Ge layer as active medium.

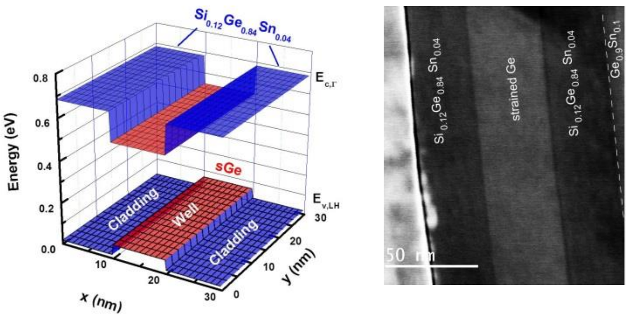

Fig. 1 (left) Band structure of a laser structure based on sGe well and $Si_{0.12}Ge_{0.84}Sn_{0.04}$ cladding and (right) the corresponding STEM image.

Large indirect band-gap $Si_{0.12}Ge_{0.84}Sn_{0.04}$ ternaries serve here as cladding layers. To achieve feasible strain values and a direct band-gap of about 0.54 eV in Ge, high Sn content GeSn or SiGeSn layers might be employed as buffer layers.

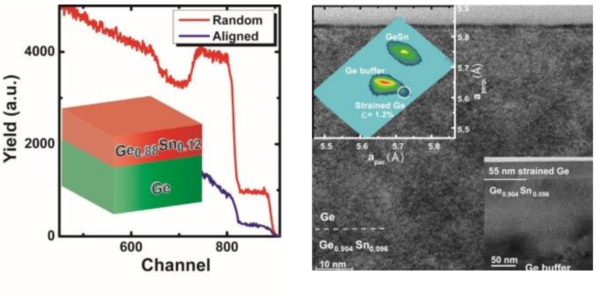

Fig 2: (left) RBS spectrum of a 300 nm $Ge_{0.88}Sn_{0.12}$ (b) HRTEM image of a 50 nm sGe on top of $Ge_{0.904}Sn_{0.96}$ and the corresponding RSM (inset).

For the epitaxial growth of (Si)GeSn non-equilibrium growth conditions have to be chosen in order to overcome the low solid solubility of Sn (<1%) in Ge. In addition, the crystal quality of the layers strongly depends on the lattice mismatch to the substrate and its surface morphology. On smooth Ge buffers, GeSn layers with up to 12 at.% Sn (Fig. 2a) were obtained with a surface rms of 1 nm. Such layers are suitable for tensile strained Ge overgrowth as shown in Fig. 2b. Reciprocal Space Mapping (RSM) of such heterostructures exhibit tensile strain levels of up to 1.2% (inset Fig. 2b) which is close to those required for the transition from an indirect to direct band-gap semiconductor. However, the strain relaxation process of GeSn layers remains challenging due to strong surface segregation of Sn even at low temperatures. A disadvantage of low band-gap GeSn buffers for Ge lasers is the high absorption and the resulting low gain. SiGeSn ternaries with high Sn content approaching a lattice constant of 5.75 Å might be a solution for the buffer growth because they exhibit an indirect band gap and are thermodynamically more stable than GeSn.

Recently GeSn was investigated as channel material for MOSFETs [10, 11] and Tunnel FETs [3]. However, the main advantage may result from combining direct and indirect band-gap of Si-Ge-Sn alloys for Tunnel-FET design, as proposed in Fig. 3. The larger $Ge_{0.9}Sn_{0.1}$ lattice, here source, induces direct band-gap transition in Ge, as channel, and thus increase the tunneling probability. In combination with an indirect $Si_{0.20}Ge_{0.76}Sn_{0.04}$ drain, ambipolar behavior and off currents can be significantly suppressed. In Fig. 3b the results of a SIMS spectrum of such a structure is presented indicating sharp interfaces and no Sn interdiffusion during growth.

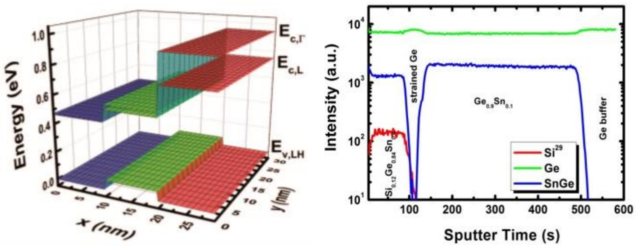

Fig. 3 (left) Band structure of a Tunnel-FET based on $Ge_{0.9}Sn_{0.1}$/sGe /$Si_{0.12}Ge_{0.84}Sn_{0.04}$ as source, channel and dreain respectively; (right) SIMS spectra of grown TFET structure.

Besides the anticipated impact on optoelectronic and electronic devices, the control of the growth of SiGeSn alloys, heterostructures, and nanostructures creates myriad opportunities to develop new nanoscale thermoelectric devices. The high mass disorder in these alloys can be exploited to control phonon transport to reduce the lattice thermal conductivity, which is a prerequisite towards the realization of efficient thermoelectrics.

4. Conclusions

The ability to grow the ternary Si-Ge-Sn class of semiconductors paves the way for new Si based applications. Photonic devices, like lasers or modulators, will become feasible due to direct band-gap of Ge/SiGeSn strained-layer heterostructures. In addition, as predicted by simulations more energy efficient devices, such as TFETs seem realistic by full exploitation of the material properties of the novel heterostructures.

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