Confinement of charge carriers in GeSn/SiGeSn heterostructures

D. Rainko[1], N. von den Driesch[1], D. Stange[1], C. Schulte-Braucks[1], G. Mussler[1], Ivan Povstugar[2], U. Breuer[2], Peter Zaumseil[3], Giovanni Capellini[3], J.M. Hartmann[4], Z. Ikonic[5], S. Mantl[1], D. Grützmacher[1] and D. Buca[1]

[1]Peter Grünberg Institute (PGI 9) and JARA-Fundamentals of Future Information Technologies, Forschungszentrum Juelich, 52425, Germany
E-mail: d.rainko@fz-juelich.de
[2]Central Institute for Engineering, Electronics and Analytics – Analytics, Forschungszentrum Juelich, Germany
[3] IHP, Im Technologiepark 25, 15236 Frankfurt (Oder), Germany
[4]CEA, LETI, MINATEC Campus and Univ. Grenoble Alpes, France.
[5]Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, UK

Abstract

In this work, we discuss carrier confinement in double heterostructures and multiple quantum well GeSn/(Si)Ge(Sn) heterostructures, aiming for efficient light emitting devices. Several heterostructures are epitaxially grown and characterized in detail concerning their structural and optical properties. Theoretical band structure calculations are used to support experimental data and provide predictions for optimized heterostructures.

1. Introduction

Over the past decades, tremendous efforts have been made to increase the performance of Integrated Circuits, while simultaneously reducing their energy consumption. Electronic photonic integrated circuits (EPICs), where information on a chip is transported via photons at the speed of light, are promising from that point of view. To combine CMOS technology with the novel concept of EPICs, monolithic integration of group IV semiconductors would be beneficial. In recent years, GeSn semiconductors emerged as an important material system in this respect, as their transition to a direct bandgap semiconductor for Sn concentrations above ~9 at.% facilitates the fabrication of laser devices [1]. Additionally, the possibility to tune their absorption and emission spectra in the short-wave infrared spectral range offers widespread applications.

Up to now lasing from group IV Sn-based semiconductors could only be achieved at temperatures below 130 K [2]. A path to improve device performance is to embed the GeSn active wells in type I heterostructures, which enhances radiative recombination by carrier confinement in the optically active material. Confinement can be optimized by introducing SiGeSn ternaries as a barrier material instead of Ge [3,4].

In this work we will present growth and characterization of multi well heterostructures based on (Si)GeSn alloys and investigate their impact on charge carrier recombination. Emphasis is put on the determination of physical parameters which will optimize light emission properties and improve laser performances.

2. Experimental

Growth and processing

To investigate the confinement of charge carriers in bulk and quantum-well materials, several GeSn/(Si)Ge(Sn) heterostructures were grown at temperatures in the range of 350 – 375 °C. Epitaxy was performed using reactive gas source epitaxy with Ge_2H_6, Si_2H_6 and $SnCl_4$ as precursors. For fabricating electrically pumped light emitting devices, B_2H_6 and PH_3 precursors were used to grow p-type and n-type doped layers. All structures were grown on top of Ge Virtual Substrates capped with partially strain relaxed GeSn buffers to reduce the compressive strain in the stacks grown on top. Double heterostructures (DHS) with thick GeSn Wells and SiGeSn barriers or GeSn/SiGeSn Multi Quantum Wells (MQWs) were used as optically active stacks to investigate carrier confinement when moving towards quantum structures. The Sn content in the wells is varied between 8.5 and 13 at.%.

Characterization

The structural properties of the samples were assessed by Atom Probe Tomography (APT), Secondary Ion Mass Spectrometry (SIMS), X-Ray Diffraction (XRD) and Rutherford Backscattering Spectrometry (RBS). RBS measurements under channeling conditions confirmed a high crystalline quality.

The influence of trapped charge carriers in the potential wells was examined by temperature dependent Photo-Luminescence (PL) or Electro-Luminescence (EL) measurements. Extracted emission maxima were compared to band energy calculations using the 8 band k·p method.

3. Results

GeSn MQWs were grown using Ge and SiGeSn as barrier materials. Elemental maps obtained from APT profiling of 20 nm $Ge_{0.92}Sn_{0.08}$/14 nm Ge and

$Ge_{0.914}Sn_{0.086}/Si_{0.105}Ge_{0.786}Sn_{0.109}$ MQWs are shown in Fig. 1. The interfaces between barriers and wells can be clearly distinguished for both types of stacks.

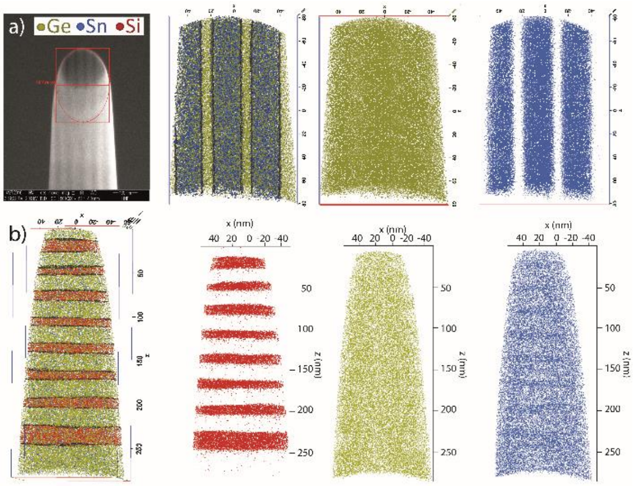

Fig. 1 APT profiles across GeSn/Ge MQW (a) and GeSn/Si-GeSn MQW (b) samples, with elemental maps for Ge, Sn and Si [4].

In recent publications [3,4], we provided evidence that introducing SiGeSn as barrier material in GeSn heterostructures strongly improves the performance of light emitting diodes. Based on band energy calculations this was attributed to confinement of charge carriers in the wells due to high band offsets. The rather small Sn content and the residual compressive strain made the GeSn wells in those samples indirect semiconductors. With the knowledge acquired from these experiments, we have grown GeSn/SiGeSn DHS and MQWs. The incorporated Sn content of 13% in the active regions yields direct bandgap semiconductor samples. Data associated with a 10 well GeSn/SiGeSn heterostructure is shown in Fig 2. The HR-XRD Reciprocal Space Map in Fig. 2a shows that GeSn wells were coherently grown on the GeSn buffer underneath, while the SIMS profile prove distinct GeSn and SiGeSn layers (Fig. 2b). From PL measurements a 30% enhanced emission for DHS as compared with bulk GeSn layers is demonstrated. Furthermore, the MQW shows a tenfold increase in light emission compared to the DHS [Fig. 2d]. So far, this indicates that introducing high Sn content quantum wells into GeSn/SiGeSn heterostructures is highly beneficial for carrier recombination and the performance of light emitting devices.

Moreover, the impact of well thickness in the MQW samples, affecting both the GeSn directness and type I band alignment, will be discussed both theoretically and experimentally (Fig. 2c).

4. Conclusions

In this contribution we present evidence for the enhanced efficiency of radiative recombination of carriers in GeSn/SiGeSn quantum wells. We compare DHS and MQW structures where Ge and SiGeSn are used as a barrier.

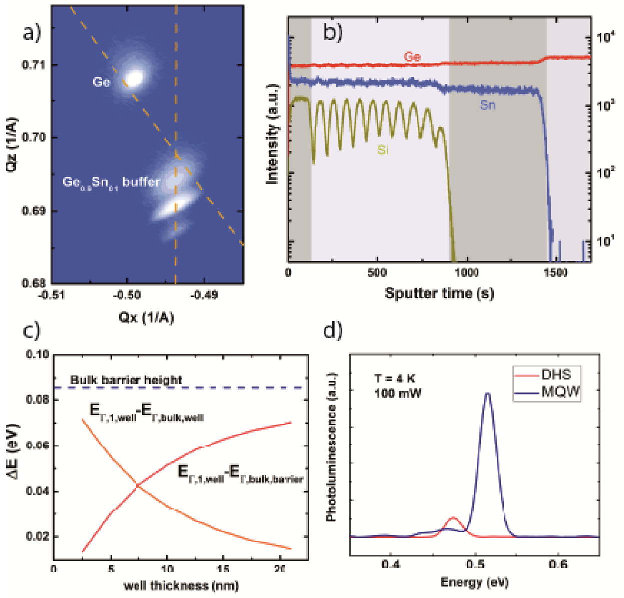

Fig. 2 a) Reciprocal space map of a GeSn/SiGeSn MQW coherently grown on a GeSn buffer. b) SIMS profiles indicate sharp interfaces between barriers and wells. c) Effective mass calculations show the influence of well thickness on confinement and quantization in the Γ valley. d) PL spectra of the DHS and GeSn/SiGeSn MQW showing a strong difference in the intensity of the PL signals at 4 K.

Acknowledgements

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References

[1] S. Wirths, R. Geiger, N. von den Driesch, G. Mussler, T. Stoica, S. Mantl, Z. Ikonic, M. Luysberg, S. Chiussi, J.M. Hartmann, H. Sigg, J. Faist, D. Buca, and D. Grützmacher, *Nature Photonics*, **9**, 88 (2015).

[2] D. Stange, S. Wirths, R. Geiger, C. Schulte-Braucks, B. Marzban, N. von den Driesch,G. Mussler, T. Zabel,T. Stoica, J.-M. Hartmann, S. Mantl, Z. Ikonic,D. Grützmacher, H. Sigg, J. Witzens and D. Buca, ACS Photonics **3**, 1279 (2016)

[3] N. von den Driesch, D. Stange, S. Wirths, D. Rainko, I. Povstugar, A. Savenko, U. Breuer, R. Geiger, H. Sigg, Z. Ikonic, J.-M. Hartmann, D. Grützmacher, S. Mantl, and D. M. Buca, *Small* (2017, in press)

[4] D. Stange, N. von den Driesch, D. Rainko, S. Roesgaard, I. Povstugar, J.-M. Hartmann, T. Stoica, Z. Ikonic, S. Mantl, D. Grützmacher and D. M. Buca, *OPTICA* (2017, in press)