Strain-engineered Ge embedded into microresonators as an active media for Si photonics

Dmitry V. Yurasov
Institute for Physics of Microstructures
Russian Academy of Sciences
Nizhny Novgorod, Russia
Inquisitor@ipmras.ru

Nikita S. Gusev
Institute for Physics of Microstructures
Russian Academy of Sciences
Nizhny Novgorod, Russia
gusevns@bk.ru

Sergey A. Dyakov
Skolkovo Institute of Science And Technology
Moscow, Russia
S.Dyakov@skoltech.ru

Alexey V. Nezhdanov
Nizhny Novgorod State University
Nizhny Novgorod, Russia
nezhdanov@phys.unn.ru

Alexey V. Novikov
Institute for Physics of Microstructures
Russian Academy of Sciences
Nizhny Novgorod, Russia
anov@ipmras.ru

Evgeny V. Skorokhodov
Institute for Physics of Microstructures
Russian Academy of Sciences
Nizhny Novgorod, Russia
evgeny@ipmras.ru

Valeriy A. Verbus
National Research University Higher School of Economics
Nizhny Novgorod, Russia
verbus@ipmras.ru

Artem N. Yablonskiy
Institute for Physics of Microstructures
Russian Academy of Sciences
Nizhny Novgorod, Russia
yablonsk@ipmras.ru

Zakhariy F. Krasil'nik
Institute for Physics of Microstructures
Russian Academy of Sciences
Nizhny Novgorod, Russia
zfk@ipmras.ru

***Abstract*—Optical properties of tensile strained n-doped Ge microstructures were investigated. Formation of microresonators based on Bragg reflectors and photonic crystals were implemented for such kind of active medium and opportunities to employ them for fabrication of efficient Si-compatible light sources were discussed.**

Keywords—Ge, strain, microresonator, photoluminescence, heat sink, lithography

I. INTRODUCTION

The lack of efficient Si-compatible light source being the main roadblock for development of Si optoelectronics has forced to seek other materials to act as an active medium. Among others germanium is the very attractive one due to full compatibility with Si-CMOS technology and direct-gap emission wavelength suitability (1.55 µm at 300K) for low loss transmission in silica fibers. However, the fundamental gap in Ge is indirect (0.66 eV at L-point) which makes the probability of radiative recombination of charge carriers rather low as compared to “true” direct-gap materials. Nevertheless the difference between the direct and indirect gaps in Ge is as small as 140 meV and it can be compensated by applying the tensile strain and/or heavy n-type doping [1]. The values of strain needed to diminish such difference down to zero and thus convert Ge into the direct-gap material are relatively high (1.6-1.9% for biaxial strain and 4.5-4.7% for uniaxial strain) that makes their achievement challenging in thick continuous layers. However various approaches were developed aiming to create such a high strains in local areas of a Ge film [1]. Recently the stimulated emission from locally strained Ge was reported at cryogenic temperatures [2, 3] with the threshold much lower than that were reported in early works in which slightly strained but heavy n-doped Ge was used [4]. However, low-threshold room-temperature lasing in Ge was not achieved yet. In this work formation and optical properties of locally strained Ge microstructures are discussed and the approaches to embed such kind of structures into various microresonators are considered.

II. EXPERIMENTAL

Blanked n-doped Ge layers of 350-400 nm thick with various doping levels were fabricated by MBE on Ge/SOI “virtual substrates” (VS). The latter were grown using the two-step growth method followed by cyclic anneal which allowed to reduce the threading dislocation density down to $5\cdot 10^7$ cm^{-2} in the VS [5]. The as-grown structures had small biaxial tensile strain (0.2-0.25%) caused by the difference in thermal expansion coefficients of Ge and Si. Than locally strained microstructures (hereafter “microbridges”) were formed using the “stress concentration” approach [1] which has led to more than one order of magnitude amplification of the initial strain in the microbridges according to micro-Raman measurements. Maskless laser lithography or electron beam lithography (EBL) followed by plasmachemical and wet chemical etching were implemented for formation of such microbridges. In order to confine the emitted light two types of cavities were used, namely Bragg reflectors and photonic crystals, which were formed using the EBL and etching mentioned above. Optical properties of the fabricated structures were studied using the micro-photoluminescence (micro-PL) measurements at 300K.

III. RESULTS

The initially fabricated microbridges represented the suspended structures as shown in Fig. 1a, which have rather poor heat sink obviously. This was the serious obstacle which hampered the obtaining of stimulated emission from such structures and the recent advances in achieving lasing from strained Ge at low temperatures were, at least in part, caused by improvement of heat dissipation [2, 3]. In these reports bonding was used at one of the fabrication stages. In this work we used the special SOI wafers with thin top Si and buried oxide layers (100 and 200 nm thick respectively) and slightly modified the etching/drying stage of fabrication in order to adhere the suspended microbridges to the underlying layers using the capillary forces of liquid [6].

Funded by Russian Science Foundation, grant № 19-72-10011.

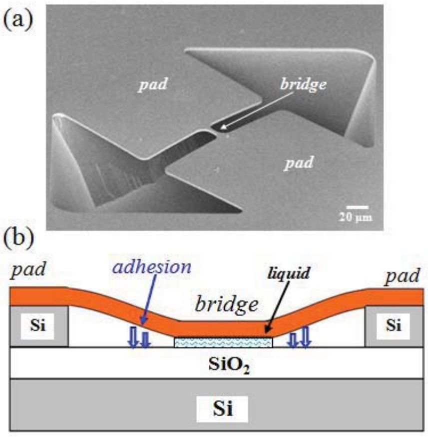

Fig. 1. (a)– Scanning electron microscopy image of suspended microbridge. (b) – scheme of the approach aimed to get the bridge adhered to substrate.

Relatively thin gap between the bridge and the substrate was surmounted by such forces and this resulted in contact between them as shown in Fig. 1b. The improved heat dissipation was confirmed by micro-Raman measurements, in particular, by the dependence of the Ge LO-phonon line on the laser power. It was obtained that increasing the probing laser power from 0.15 to 5.8 mW leads to the significant additional shift of this line for suspended bridge corresponding to more than 100 K increase of its local temperature, but for the adhered bridge the local heating was as small as 15-18 K. Note that adhesion of the bridge didn't lead to any change of its strain.

Micro-PL studies have shown the significant increase of integrated PL signal and the emission redshift from the bridges as compared to blanked Ge film in accordance with theoretical expectations (Fig. 2). Power-dependent PL measurements have shown the superlinear dependence of integrated PL intensity on pumping power. It was also revealed that bridges adhered to the oxide layer burn if the pumping power is 4-5 times higher than in the case of suspended bridges while bridges adhered to Si could stand even higher pumping power densities of the order of MW/cm^2 (the highest accessible power in used PL setup) without any failure.

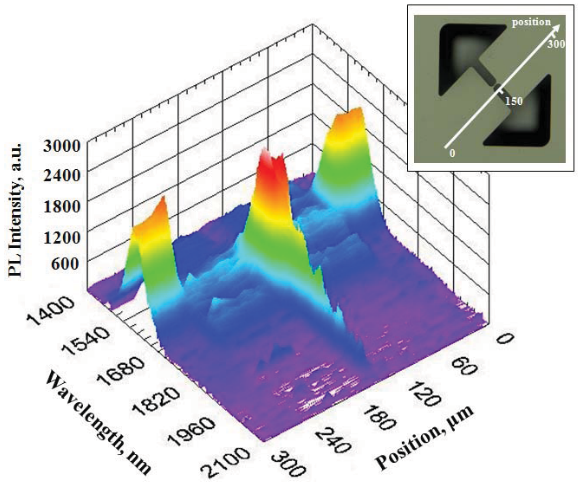

Figure 2. 3D image showing PL spectra at different positions, including strained bridge, pads and undisturbed Ge film. Top view of the structure indicating at which point the PL was measured ("position" coordinate) is shown in the inset.

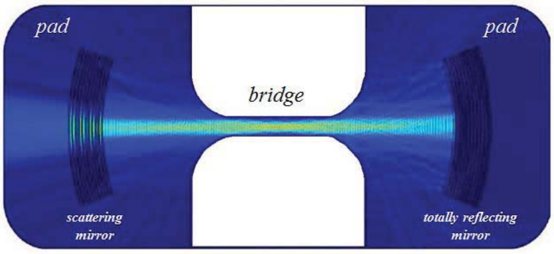

Fig. 3. Schematic view of Bragg reflectors inside the pads. Electric field distribution is shown by color.

In order to create the cavity suitable for the locally strained Ge microbridges as gain medium theoretical modeling of two types of cavities was performed (Fig. 3). Finite element method (FEM) was used to determine the design of Bragg reflectors (one is ~100% reflecting mirror and other is more complex, designed for light scattering). Parameters of such reflectors were chosen as such to minimize their influence on strain distribution inside the bridge. The results of modeling are shown in Fig. 3, where microbridge with two mirrors in the pads is shown along with electromagnetic field distribution.

Rigorous coupled wave analysis (RCWA) was used to calculate the parameters of photonic crystal resonator, situated inside the bridge, in order to achieve the resonant emission enhancement. The latter could be reached in "cavity-less" photonic crystals due to coupling of the radiative modes located in the vicinity of the Γ-point of the photonic crystal Brillouin zone which are characterized by the low group velocity. Application of such kind of a resonator to the strained microbridges is discussed.

IV. CONCLUSIONS

In this work fabrication and optical properties of locally strained Ge microstructures with improved heat dissipation were reported. Significant PL enhancement along with the emission redshift was observed. Rather easy way to remarkably improve the heat sink from such structures was realized. Different designs of microresonators suitable for such kind of active medium were considered. Implementation of the proposed schemes seems to be promising in order to realize an all-group IV infrared light source.

REFERENCES

[1] R. Geiger, T. Zabel and H. Sigg, "Group IV direct band gap photonics: methods, challenges, and opportunities", Front. Mater., vol. 2, art. 52, (2015).

[2] S. Bao, D. Kim, C. Onwukaeme, S. Gupta et.al.,"Low-threshold optically pumped lasing in highly strained germanium nanowires" Nat. Commun., vol. 8, art. 1845, (2017).

[3] A. Elbaz, M. El Kurdi, A. Aassime, et.al., "Germanium microlasers on metallic pedestals", APL Photon.vol. 3, pp. 106102-9 (2018).

[4] J. Liu, X. Sun, R. Camacho-Aguilera, L.C. Kimerling, and J. Michel, "Ge-on-Si laser operating at room temperature", Opt. Lett., vol. 35, pp. 679-681, (2010).

[5] D. V. Yurasov, A. I. Bobrov, V. M. Daniltsev, et.al., "Impact of Growth and Annealing Conditions on the Parameters of Ge/Si(001) Relaxed Layers Grown by Molecular Beam Epitaxy", Semiconductors, vol. 49, pp.1415-1420, (2015).

[6] N. Tas, T. Sonnenberg, H. Jansen, R. Legtenberg and M. Elwenspoek, "Stiction in surface micromachining", J. Micromech. Microeng., vol. 6, pp. 385-397 (1996).