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(Digital Presentation) Epitaxially Grown of SiGe on Ge Microbridge and Observation of Strong Resonant Light Emission

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Fabrication of branch-like bridges based on Ge-on-Si (110) and observation of resonant light emission

Takahiro Inoue, Youya Wagatsuma, Reo Ikegaya, Ayaka Odashima, Masaki Nagao, Kentarou Sawano

Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya-ku, Tokyo 158-0082, Japan

Corresponding author: g2291201@tcu.ac.jp

We observe strong room-temperature photoluminescence from Ge microbridges formed on Ge-on-Si (110). The Si (110) substrate is employed to fabricate the bridge along [111] direction as uniaxial strain in the [111] direction is expected to be the most effective to bring direct transition. In this study, we grow Ge-on-Si with (110) orientation and fabricate MB along the [111] directions. Due to the low etching rate of the (111) plane, however, etching of the Si under the square-shaped pads is quite difficult. By contrast, we fabricate branch-like MB, where the underneath Si was fully etched owing to the various directions of the etching. As a result, we obtained very strong resonant light emission.

1. Introduction

Silicon (Si) photonics has become a promising platform for optical interconnections owing to its advantages, such as high data transfer rate, low power consumption and compatibility to Si complementary metal oxide semiconductor (CMOS) technology [1, 2]. However, due to its indirect band gap nature, Si is not a proper material as a light source for the Si photonics. In this context, Germanium (Ge)-based light sources have been emerged as one of promising candidates [3-5] since introduction of tensile strain boosts the direct transition probability via reduction of the Γ-valley, resulting in an increase in luminescence efficiency. By epitaxial growth of the Ge directly on the Si (Ge-on-Si), the tensile strain can be induced in the Ge layer due to the difference in thermal expansion coefficients between Ge and Si. Amounts of the tensile strain induced in the Ge-on-Si, however, have not sufficiently large, around 0.2%. The methods of introducing tensile strain using compound semiconductors have reported. [6,7]. However, compound semiconductor substrates have not suitable for light-emitting device integration on silicon substrates. So as to increase the strain amount, fabrication of Ge microbridge (MB) structure was recognized as one of the most promising ways. It was shown that the uniaxial tensile strain can be largely enhanced in the MB, offering further improved luminescence efficiency [8-13]. There are several reports on light emitting diode devices based on Ge MB structures [14, 15]. In these reports standards Si (100) substrates have used and bridge directions were set to be <001> direction. However, band shift of the Γ-valley via the tensile strain is expected to be the largest in the <111> directional uniaxial strain, according to calculations [16]. In this study, therefore, we fabricate strained Ge MB structure along the <111> direction with using a Si (110) substrate. Both ends of the MB are connected to so-called square pads, which are also floated like the MB and can provide large tensile strain in the MB. Due to the low etching rate of the (111) plane, however, etching the Si under the pads is quite difficult [17]. For this reason, we fabricate branch-like MB, where pads are formed by branch-like Ge as narrow as the MB. We obtain strong peaks and resonant peaks in photoluminescence spectra from the fabricated Ge MB. With respect to this resonance phenomenon, we have elucidated that it originates from the bridge aspect [18].

2. Experimental procedures

Ge layers were directly grown on a 3-inch Si (110) wafers by solid-source molecular beam epitaxy (MBE) by a two-step growth method [19,20]. First, a low temperature Ge layer (Tg = 350°C, 40 nm) and a high temperature Ge layer (Tg = 550°C, 500 nm) were successively grown and subsequently annealed at 800°C for 10 min. to improve the crystallinity. Then, patterning of the MB structures as shown in Fig. 1 was performed by standard photolithography process. The structure consists of the microbridge with the width and length of 8μm. Next, the grown Ge and the underlying Si substrate were etched down by reactive ion etching (RIE) with using etching gases of CF_4, SF_6 and O_2. After the etching down to the Si substrate, the Si underneath the MB was removed to form freestanding structures by selective etching of the Si with KOH + H_2O solution.

Micro-photoluminescence (μ-PL) and Raman spectroscopy measurements were performed at the center of the MB structure at room temperature. For μ-PL measurements, 980 or 532 nm continuous-wave pump laser was used with a pump power of 2 mW, and the laser spot diameter is about 2–3 µm. For Raman an excitation laser with a wavelength of 514 nm and a power of 1 mW was used and the laser spot diameter was about 1 µm.

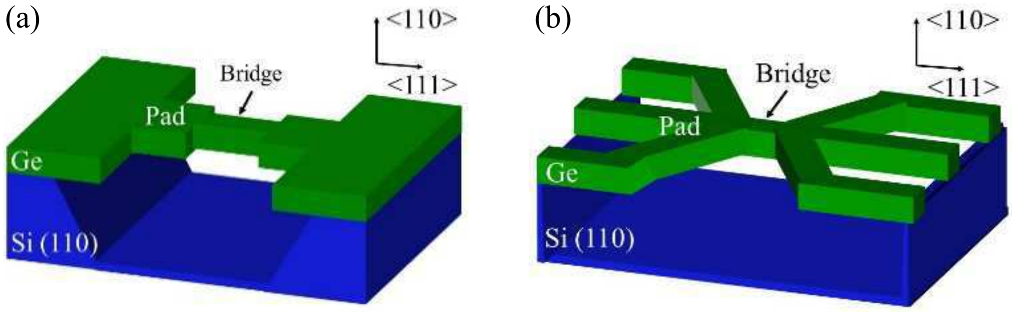

Fig. 1 Schematics of Ge microbridges with (a) square-pads and (b) branch-like pads fabricated in this study.

3. Results and discussions

Figures 2 show SEM images of the fabricated MBs with the square-pads and branch-like pads. It is found that branch-like pads are completely floated and no deflection of the MB portion due to the etching of the lower portion of the MB is observed. On the other hand, for MB with the square-pads, the Si under the pads is seen to remain un-etched and (111) planes appear. This result is attributed to the low etching rate of the (111) planes. It is demonstrated that the employment of the branch-like pads enables etching of the underneath Si from various directions, resulting in the full etching without appearance of the (111) planes.

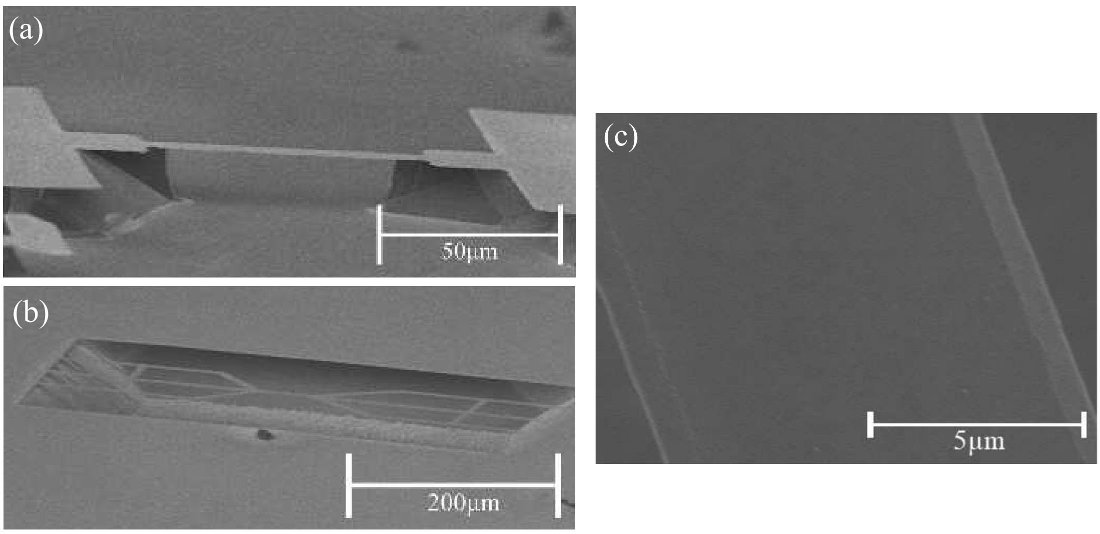

Fig. 2 SEM images of (a)Square-pad and (b)Branch-like and (c)Center of Branch-like microbridge.

Figure 3 shows the room temperature PL spectra for Ge MB with the square-pads and branch-like pads. The 980 nm pumping laser was used here. Whilst almost no PL signal is obtained from the Ge-on-Si (110) before the processing, it is clearly found that strong PL signals appear after the fabrication of the MB. Particularly, for the MB with branch-like pads, the PL intensity is greatly enhanced and several periodic peaks are observed from 1800 to 2000 nm. These peaks are considered to come from Fabry-Perot resonances realized by reflection via the bridge side walls [18]. Simple calculations of Fabry-Perot resonant modes roughly agree with the obtained peaks, where the cavity length used for the calculation is 8.0 and 9.7 μm, which corresponds to the bridge widths. Detailed SEM observations confirmed that the Ge MB is formed to be convex-shape as shown in Fig.2 (c). It is speculated that the resonant peaks coming from the upper and lower parts of the MB were overlapped.

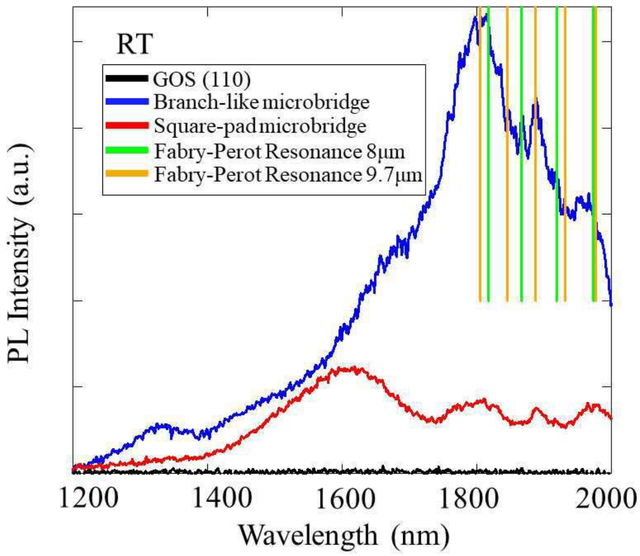

Fig. 3 Room temperature PL spectra of square-pad microbridge and branch-like microbridge and unprocessed Ge-on-Si. Fabry-Perot resonant peaks are indicated.

A Raman spectrum obtained from the central parts of the branch-like microbridge is shown in Fig. 4 along with spectra for the bulk Ge and un-processed Ge-on-Si (110). The strain rate of the GOS fabricated in this study was 0.1% and the branch-like microbridge was 0.3%. Thus, it can be said that an increase in strain rate was attained by the fabrication of branch-like microbridges.

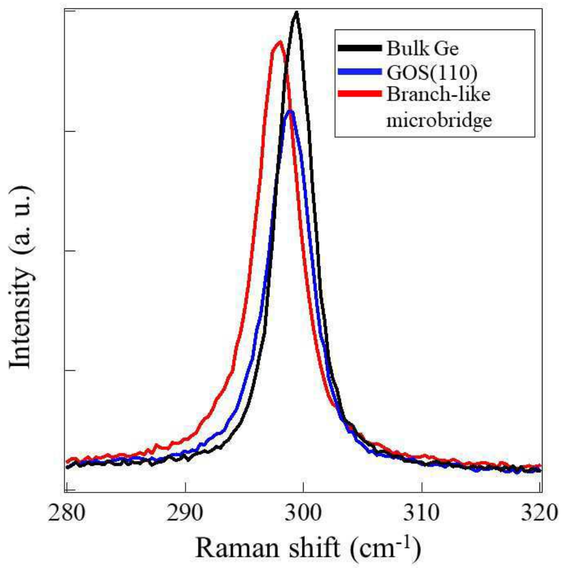

Fig. 4 Raman spectra for Bulk Ge, Ge-on-Si (GOS)Branch-like microbridge.

4. Conclusions

In this study, uniaxially tensile-strained Ge microbridge (MB) structures were fabricated based on the strained Ge epitaxially grown on a Si (110) substrate (Ge-on-Si). The fabrication of the branch-like microbridge enabled the full etching of underneath Si during selective etching with KOH. Significant enhancements in the PL intensity were obtained from the branch-like microbridge compared with the unprocessed Ge-on-Si and square-pad microbridge. Moreover, strong resonant peaks were observed from the branch-like microbridge. It demonstrates that Ge branch-like MBs can be applied to highly efficient Ge light emitters.

5. Acknowledgments

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[1] Y. A. Vlasov, IEEE Commun. Mag. 50 (2), S67 (2012).
[2] D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Virot, J. M. Fédéli, J. M. Hartmann, J. H. Schmid, D.-X.

Xu, F. Boeuf, P. O'Brien, G. Z. Mashanovich, and M. Nedeljkovic, J. Opt. 18, 073003 (2016).
[3] J. Liu, Photonics 1, 162 (2014).
[4] R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, and J. Michel, Opt. Express 20, 11316 (2012).
[5] R. Koerner, M. Oehme, M. Gollhofer, M. Schmid, K. Kostecki, S. Bechler, D. Widmann, E. Kasper, and J. Schulze, Opt. Express 23, 14815 (2015).
[6] Yijie Huo, Hai Lin, Robert Chen et al., 2011 Appl. Phys. Lett. 98, 011111.
[7] Qimiao Chen, Liyao Zhang Yuxin Song et al., 2021 ACS Appl. Nano Mater, 4, 897-906.
[8] Shuyu Bao, Daeik Kim, Chibuzo Onwukaeme et al., 2017 Nat Commun 8, 1845 .
[9] M. J. Süess et al., 2013 Nat. Photonics 7, 466(2013).
[10] Donguk Nam et al., Nano Lett. 2013, 13, 3118−3123.
[11] A. Gassenq et al., Appl. Phys. Lett. 108, 241902 (2016).
[12] David S. Sukhedeo et al., Photon. Res. 2014, Vol. 2, No. 3.
[13] Peiji Zhou et al 2018 Jpn. J. Appl. Phys. 57 04FH10
[14] Jialin Jiang et al., 2019 ACS Photonics, 10.1021.
[15] Senbiao Qin et al., Nanophotonics 2021; 10(11): 2847–2857.
[16] H. Tahini et al., J. Phys.: Condens. Matter 24, 2012.
[17] Byungwook Kim et al., 1998 J. Electrochem. Soc. 145 2499.
[18] T. Inoue et al, 2022 Journal of Crystal Growth 590 (2022) 126
[19] H. C. Luan, D. R. Lim, K. K. Lee, K. M. Chen, J. G. Sandland, K. Wada, and L. C. Kimerling, Appl. Phys. Lett. 75, 2909 (1999).
[20] K. Nishida, X. Xu, K. Sawano, T. Maruizumi, and Y. Shiraki, Thin Solid Films 557, 66 (2014).