Laser-assisted material composition engineering of SiGe planar waveguides

Antoine F. J. Runge[1,*], Yohann Franz[1], Callum G. Littlejohns[1,2], Katarzyna Grabska[1], Sakellaris Mailis[1],
Frederic Y. Gardes[1], and Anna C. Peacock[1]
1. Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK
2. Silicon Centre of Excellence, Nanyang Technological University, 639798, Singapore
*a.f.runge@soton.ac.uk

Abstract—**We report the compositional engineering of silicon-germanium planar microstructures through laser processing. The effects of the laser treatment are assessed through microscope imaging and Raman spectroscopy. Our results reveal that the laser-exposed regions display a significant change in the material composition.**

Keywords: Semiconductor materials; Laser material processing; Optoelectronics.

I. INTRODUCTION

Semiconductors have emerged as excellent optical materials, allowing for the experimental demonstration of a wide range of integrated photonics devices over the last decade [1, 2]. The advantages of these materials include large transparency windows in the mid-IR, strong light confinement, large nonlinear coefficients and high optical damage thresholds [3]. So far, silicon (Si) remains the most widely used material, but recently significant efforts have been devoted to the development of silicon-germanium (SiGe) alloys [4, 5]. As well as offering an extended transparency window, this composite material also has higher hole and electron mobility than Si that allows for the fabrication of optoelectronic devices with faster speeds [6]. More interestingly, the electronic bandgap and optical properties of the $Si_{1-x}Ge_x$ alloy can be changed significantly by adjusting the material composition through x. For example, SiGe materials can be either absorbing or transparent at telecommunications wavelengths depending on the concentration of germanium (Ge) in the alloy.

Although the material composition of photonic SiGe structures has, to date, been typically determined by the diffusion temperature used during the fabrication process [5], recently a new technique was demonstrated that allowed for the micro-composition tuning within SiGe fibers [7]. Specifically, the composition of the fiber was locally modified through the absorption of CO_2 laser radiation, where the Ge material was pulled toward the high temperature spot to create Ge rich micro volumes. This technique allows for the fabrication of complex micro structures in semiconductor fibers, opening the door to applications such as gratings or heterojunctions. However, the demonstration of this technique for planar platforms has yet to be made.

In this work, we report the compositional modification of SiGe planar microstructures using continuous wave (c.w.) laser radiation. The sample areas that have been treated by laser light display a noticeable change in reflectivity, indicating a change in the material. Micro-Raman spectroscopy of these areas reveals that this optical change corresponds to a strong compositional modification of the material and the creation of Ge rich micro volumes.

II. SAMPLE FABRICATION AND EXPERIMENTAL SETUP

The starting SiGe samples used in this work were fabricated using a rapid melt growth process similar to the one described in [5]. Specifically, a silica layer is deposited on a crystalline silicon (c-Si) substrate and openings are patterned to reveal seed areas of exposed c-Si. A 400 nm Ge layer is then deposited by plasma-enhanced chemical vapor deposition (PECVD) and patterned into the desired structure. Another silica layer is added to encapsulate the Ge areas. Subsequently, using a furnace the sample is heated above the melting temperature of Ge. During this process, Si diffuses from the seed into the Ge layer. The amount of Si in the final SiGe alloy is determined by the diffusion temperature used. Finally, the samples are cooled down, triggering the recrystallization of the liquid SiGe alloy, emanating from the Si seed, to form single crystal SiGe. The resulting structures are 4 µm wide and 400 nm thick with a Ge concentration of ~50 at% (i.e., x=0.5).

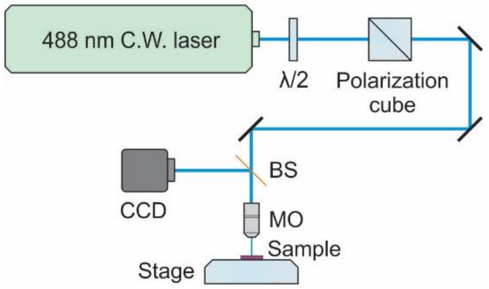

Figure 1. Experimental setup. BS, beam splitter; MO, microscope objective.

The samples are then exposed to laser radiation using the setup schematized in Fig. 1 [8]. The laser is an argon ion source emitting c.w. light at 488 nm and the optical power was adjusted using a combination of a half wave plate and a polarization cube splitter. The laser beam is then focused on the SiGe waveguide using a 20x microscope objective, producing a spot with a diameter of 2.5 µm on the sample surface. Finally, a pellicle beam splitter and CCD camera were used to image the sample surface and control its position using a set of linear micro-precision stages.

III. RESULTS AND DISCUSSION

The SiGe structures were exposed to laser light for a duration of 10 s and an optical power of 85 mW, leading to an intensity on the sample surface of 1.7 MW/cm^2. This process was repeated several times at positions separated by 10 µm, along the SiGe ridge. For this combination of power and duration, sufficient energy was transferred to the sample to melt the SiGe material. As described in [7], the Ge is pulled toward the high temperature spot while the Si is pushed away.

To assess the effects of the laser treatment, we first inspect the top surface of the processed sample under a microscope. Images of the SiGe structure before and after laser processing are shown in Fig. 2(a) and (b), respectively. As seen in Fig. 2(a), the samples initially display a relatively homogeneous surface color, while the surface after laser processing displays bright circles with a 1.5 µm diameter, separated by 10 µm, indicating a change in the material structure where the laser intensity is at its highest.

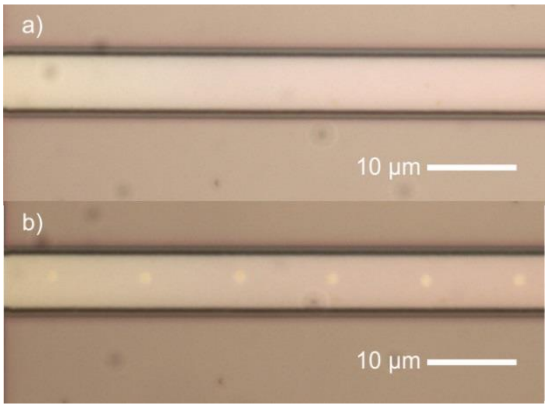

Figure 2. Microscope images of the SiGe sample top surface before (a) and after (b) laser processing.

To gain more insight on the material composition of the sample, we performed a set of micro-Raman spectroscopy measurements on the sample surface before and after laser exposure. The recorded spectra are shown in Fig. 3. The starting material (blue) displays four different Raman peaks centered at 288, 406, 480 and 520 cm^{-1}, and corresponding to Ge-Ge, Si-Ge, amorphous Si and c-Si, respectively. After the laser processing (orange) the Raman spectrum displays one single peak corresponding to the Ge-Ge bond vibration, confirming a the change in the local material composition. We also note the Ge-Ge peak is narrower and redshifted after laser exposure, indicating that the Ge material is recrystallizing as it cools down after being pulled toward the high temperature spot. As the relative Si content is reduced, the strain decreases and allows for the formation of higher quality Ge crystal.

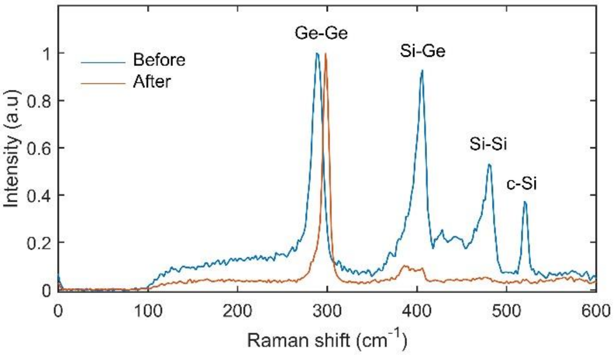

Figure 3. Raman spectra of the SiGe structure, before (blue) and after (orange) laser processing. The corresponding material vibrations are indicated on top of the peaks.

IV. CONCLUSION

We report a laser processing procedure to engineer the composition of planar SiGe microstructures via laser-induced localized heating of the material. The laser-treated surface displays a strong visual indication of local refractive index change due to the increased concentration of high index Ge in the treated area, as confirmed by Raman spectroscopy. Our technique allows for highly localized tuning of the material composition to control the optoelectronic properties, such as the optical transmission, which could be used for the production of gratings and heterojunctions.

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