Laser Processing of Amorphous Semiconductors on Planar Substrates for Photonic and Optoelectronic Applications

Ozan Aktas[1,*], Yohann Franz[1], Antoine F. J. Runge[2], Stuart J. MacFarquhar[1], Swe Z. Oo[3], Vinita Mittal[3], Antulio Tarazona[1], Harold M. H. Chong[3], Sakellaris Mailis[4], and Anna C. Peacock[1]

[1]Optoelectronics Research Centre, University of Southampton, Southampton, UK
[2]Institute of Photonics and Optical Science (IPOS), School of Physics, University of Sydney, Sydney, Australia
[3]School of Electronics and Computer Science, University of Southampton, Southampton, UK
[4]Department of Photonics and Quantum Materials, Skolkovo Institute of Science and Technology, Moskovskiy, Russia
*corresponding author, E-mail: O.Aktas@soton.ac.uk

Abstract

We report results of laser processing on amorphous silicon and silicon-germanium films deposited on planar substrates. Pre-patterned a-Si waveguides were recrystallized and reflowed to enhance their material and optical properties. Formation of millimeter long crystal grains and surface roughness of 0.52 nm enable optical losses to become as low as 5.3 dB/cm. Laser-driven phase separation in the binary alloy of a-SiGe allows fabrication of composition graded microstructures with Si-rich and Ge-rich regions. A composition tuning capability of 40% was demonstrated.

1. Introduction

Polycrystalline semiconductor materials have the potential to exhibit both optical and electronic functionalities that are comparable with single crystal platforms, but with much more flexibility in the fabrication process. However, to obtain good quality of polycrystalline materials, the process temperatures need to be higher than 900 ºC [1], rendering them incompatible with CMOS devices. We have developed a laser processing method for the fabrication of low loss p-Si waveguides with a low thermal budget [2].

Another set of material for laser processing is binary semiconductor alloys such as SiGe, which have attracted a growing interest of the photonics industry over the past few years, due to their tunable material, electrical and optical properties. Bandgap and optical properties of $Si_{1-x}Ge_x$ can be modified by changing the material composition through x [3]. Laser inscription of compositional microstructures in crystalline SiGe core silica clad fibres has been recently shown during the local heating of the core by a CO_2 laser [4]. However, spatial control of the phase separation in SiGe alloys for fabrication of photonic devices has yet to be demonstrated on planar substrates.

2. Fabrication

The fabrication process of a-Si films begins with the formation of a 4.6 µm thick thermally grown buried oxide layer on top of the c-Si substrate. A thin film of a-Si with a thickness of 480 nm is then grown using a hot-wire chemical vapor deposition (HWCVD) technique with silane (SiH_4) as the only precursor. HWCVD allows low temperature deposition at 320 ºC with low hydrogen concentration. Following the deposition, e-beam lithography and plasma etching were used to pattern a series of straight waveguides with widths of 0.5 µm, 1 µm, 1.5 µm and 2 µm in the a-Si film.

The a-SiGe films were directly fabricated on silicon wafers, which were dipped in buffered hydrofluoric acid (HF) for 3 minutes to remove the native oxide before deposition. Then, 400 nm thick SiGe films were deposited by plasmon enhanced chemical vapour deposition (PECVD) using SiH_4 (5 sccm) and GeH_4 (50 sccm) precursors with an RF power of 15 W at a pressure of 300 mTorr and a temperature of 200 ºC. Initial atomic content of Ge is 60%.

3. Laser processing

Laser processing of a-Si and a-SiGe films was carried out with the setup shown in Figure 1. The light source is an Argon ion laser emitting continuous wave (CW) radiation at 488 nm with a maximum power of 350 mW. The setup includes 3D motorized stages capable of programmed movements at speeds ranging from 0.01 mm/s up to 100 mm/s. The power was adjusted using a polarization cube and a half wave plate. The beam was focused on the top surface of the samples using 10x and 20x objective lens to produce a spot diameter of 4.7 µm and 2.5 µm, respectively. A pellicle beam splitter, a CCD camera and a white light source were used to image the surface of the samples.

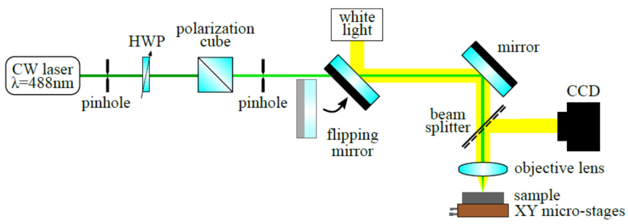

Figure 1: Schematic of experimental set-up for laser processing. HWP is half-wave plate.

4. Material and optical characterizations

Micro focus X-ray diffraction (XRD) with a highly collimated beam provided by a synchrotron source was used to assess the presence of crystals in the laser-processed regions and collect information about their length, orientation and lattice constant. The XRD setup was established in a grazing incidence configuration to avoid strong diffraction from the c-Si substrates. In addition, X-ray fluorescence spectroscopy was used to access spatial distribution of Ge in the p-SiGe tracks. We also performed a set of micro-Raman spectroscopy measurements before and after laser processing. The line width of the Raman peaks were used to optimize power levels and scan speeds. The optical quality of the p-Si waveguides was assessed by measuring the linear propagation losses using the standard cut-back technique.

5. Results and Discussion

5.1. Laser crystallization and reflowing of amorphous silicon waveguides

As a consequence of the complete melting during laser annealing, the a-Si waveguides were reshaped while in liquid state by surface tension that acts on the liquid-air interface. Therefore, the initially rectangular cross section of the a-Si waveguide forms a semi-circular shape, as shown in Figure 2. Here, the SEM micrograph in (a) is an un-processed 2 µm wide a-Si waveguide, whilst the SEM micrograph in (b) is a 2 µm wide p-Si waveguide, which has been laser processed with 200 mW at 0.1 mm/s.

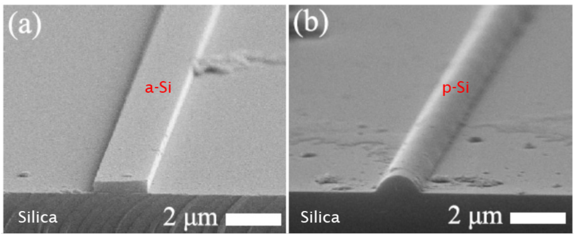

Figure 2: SEM micrographs shows cross-section of a 2µm wide waveguide before (a) and after (b) laser processing.

Micro-Raman spectroscopy, Secco etching and X-ray diffraction measurements reveal the high crystalline quality of the processed waveguides with the formation of millimeter long crystal grains. Optical losses as low as 5.3 dB/cm have been measured, indicating their suitability for the development of integrated circuits.

5.2. Laser inscription of composition graded polycrystalline silicon-germanium microstructures

Laser assisted melting of SiGe alloys induces phase segregation of Si and Ge atoms producing Si-rich and Ge-rich regions. Our results show that the spatial profile and amount of phase segregation in the Si-Ge thin films can be engineered by controlling the scan speed of the laser. Depending on the scan speed, two different types of spatial redistribution for Ge can be achieved as shown in Figure 3. Speeds below a threshold (5 mm/s) result in Si-rich regions at the centre of the track. However, above the threshold speed, a Ge-rich region is obtained at the centre between two lower index Si-rich lateral regions, which can help to promote optical waveguiding in the Ge-rich core. Moreover, higher Ge content can be obtained by using higher scan speeds. We have control over the size, composition gradient and direction of p-SiGe microstructures written by the laser.

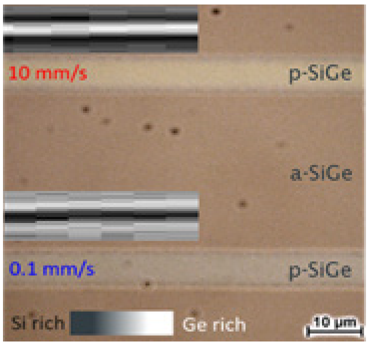

Figure 3: Optical microscope image shows two polycrystalline tracks inscribed in an amorphous SiGe film on c-Si wafer by a CW Ar+ ion laser at different scan speeds. Inset pictures show speed dependent spatial redistribution of Ge as given by the X-ray fluorescence intensity of Ge.

6. Conclusions

We have demonstrated laser processing of amorphous semiconductors on planar substrates to fabricate low loss p-Si waveguides and composition graded p-SiGe microstructures. A key feature of our technique is the low thermal budget, which makes it compatible with CMOS fabrication processes. Laser processing of semiconductors can pave the way for various photonic and optoelectronic devices to be used in novel integrated platforms.

Acknowledgements

The authors thank Diamond Light Source staff for their assistance on beamline I18, and the Engineering and Physical Sciences Research Council (EPSRC) for funding.

References

[1] J. S. Orcutt, S.D. Tang, S. Kramer, K. Mehta, H. Li, V. Stojanovic, Low-loss polysilicon waveguides fabricated in an emulated high-volume electronics process, *Opt. Express* 20: 7243−7254, 2012.

[2] Y. Franz, A. F. J. Runge, Swe Z. Oo, G. Jimenez-Martinez, N. Healy, A. Khokhar, A. Tarazona, H. M. H. Chong, S. Mailis, A. C. Peacock, Laser crystallized low-loss polycrystalline silicon waveguides, *Opt. Express* 27: 4462-4470, 2019.

[3] G. Pethuraja, R. Welser, A. Sood, C. Lee, N. Alexander, H. Efstathiadis, P. Haldar, J. Harvey, Effect of Ge Incorporation on Bandgap and Photosensitivity of Amorphous SiGe Thin Films, *Mater. Sci. and Appl.* 3: 67-71, 2012.

[4] D. A. Coucheron, M. Fokine, N. Patil, D. W. Breiby, O. T. Buset, N. Healy, A. C. Peacock, T. Hawkins, M. Jones, J. Ballato, U. J. Gibson, Laser recrystallization and inscription of compositional microstructures in crystalline SiGe-core fibres, *Nat. Commun.* 7: 13265, 2016.