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Laser processed semiconductors for integrated photonic devices -INVITED

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Abstract. We report results of laser processing of amorphous silicon and silicon-germanium semiconductor materials for the production of integrated photonic platforms. As the materials are deposited and processed at low temperatures, they are flexible, low cost, and suitable for multi-layer integration with other photonic or electronic layers. We demonstrate the formation of waveguides via crystallization of pre-patterned silicon components and functional microstructures through crystallization and compositional tuning of silicon-germanium alloy films. These results open a route for the fabrication of high density, multi-functional integrated optoelectronic chips.

1 Introduction

Group IV semiconductor materials such as silicon (Si) and germanium (Ge) are excellent materials for integrated photonic devices as they are CMOS compatible, have high refractive indices, which allows for small device footprints, and they offer the potential for integration with electronics [1]. Currently, most of the focus on these materials is on single-crystal platforms, owing to the superior optical and electronic properties over their amorphous and polycrystalline counterparts. However, single-crystal platforms still face significant integration challenges, for example in multi-layer and multi-material systems, due to fabrication and growth constraints. Thus, more recently there has been increased interest in Group IV materials that can be deposited using cheap and flexible methods, followed by annealing to achieve high quality, i.e., close to single-crystal, polycrystalline components [2].

Here we report results on two different Group IV material platforms that can be produced via deposition followed by laser crystallization. Compared to conventional thermal annealing treatments, laser crystallization offers a key advantage in that it is highly localized, so that the heating and crystallization can be confined to individual components, reducing the overall thermal budget. In our first demonstration, we show that it is possible to produce high quality poly-Si waveguides by laser processing pre-patterned amorphous Si (a-Si) components that have been deposited at temperatures < 400 ºC [3]. For the second demonstration, we focus on the crystallization and compositional tuning of amorphous SiGe (a-SiGe) alloy films deposited at ~200 ºC. Here, the added advantage of composition tuning is critical as it allows for direct laser writing of graded index microstripes, which could be exploited for the production of optoelectronic circuits and components (e.g., waveguides, gratings, modulators) with tunable functionality [4].

2 Materials deposition

The fabrication of the a-Si components begins with the formation of a 4.6 µm thick thermally grown buried oxide layer on top of a c-Si substrate. A 480 nm thick film of a-Si is then grown using a hot-wire chemical vapor deposition (HWCVD) technique, with silane (SiH_4) as the only precursor, at a temperature of 320 ºC. 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 c-Si wafers, which were dipped in buffered hydrofluoric acid (HF) for 3 minutes to remove the native oxide. The 400 nm thick SiGe films were deposited by plasma 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. The initial atomic content of Ge is 60%.

3 Laser processing

Laser processing of the a-Si and a-SiGe samples was carried out with the setup shown in Fig. 1. The light source was an Argon ion laser emitting continuous wave (CW) radiation at 488 nm with a maximum power of 350 mW. The setup included 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

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polarization cube and a half wave plate. The beam was focused on the top surface of the samples using either a 10x or 20x objective lens to produce spot diameters 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. In both cases the samples were heated with the laser until melting of the semiconductor occurred.

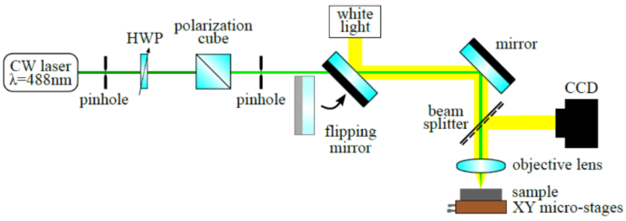

Fig. 1. Laser writing setup. HWP is half-wave plate.

4 Results and discussion

4.1 Laser crystallization of a-Si waveguides

For processing of the a-Si components, the waveguides were heated until complete melting. As a consequence, the waveguides are reshaped while in a 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 in the poly-Si form, as shown in Fig. 2. Here, the SEM micrograph in (a) is an un-processed 2 µm wide a-Si waveguide, and in (b) is a 2 µm wide poly-Si waveguide, processed with a power of 200 mW at a speed of 0.1 mm/s.

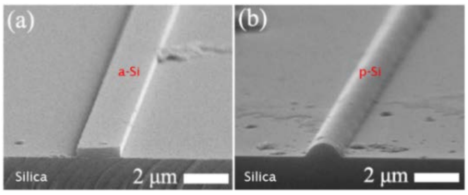

Fig. 2. SEM micrographs showing cross-sections of a 2µm wide waveguide before (a) and after (b) laser processing.

Micro-Raman spectroscopy, Secco wet 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 [3].

4.2 Laser crystallization and compositional tuning of a-SiGe films

Laser assisted melting of SiGe alloy films induces phase segregation of the 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 SiGe thin films can be engineered by controlling the scan speed of the laser. Depending on the speed, different spatial redistributions of the alloy components can be achieved, as shown in Fig. 3.

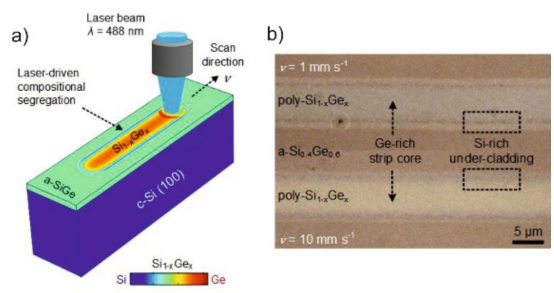

Fig. 3. a) Schematic of compositional tuning to produce crystalline microstripes. b) Optical microscope image shows two polycrystalline stripes, written with difference speeds, and hence Ge concentrations.

Speeds below a threshold of 5 mm/s result in a small compositional segregation within the solidified region, shown by the darker central stripe in Fig. 3b. Note, the Ge content on the top surface is slightly higher than the initial composition. However, above this threshold, 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. By changing the spot size and power, we have control over the size, composition gradient, and shape of the poly-SiGe microstructures written by the laser. Importantly, compositional tuning allows for modifying the refractive index and bandgap of the material, which is useful in the construction of gratings, modulators and detectors that can operate over different wavelength ranges [4].

5 Conclusion

We have demonstrated laser processing of amorphous silicon waveguides and silicon-germanium films for the construction of integrated photonic devices. A key feature of our technique is that the materials are produced using low cost, low temperature and flexible deposition methods, making the components compatible with multi-layer and multi-material architectures.

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