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Direct bandgap GeSn alloys for laser application

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Abstract: Efforts towards development of monolithically integrated silicon-compatible lasers have been revitalized since the demonstration of optically pumped GeSn waveguide lasers. Here we investigate the laser emission of GeSn alloys by means of waveguide and microdisk photoluminescence.
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1. Introduction

Group IV photonics, i.e., silicon based Electronic Photonic Integrated Circuits (EPICs), provides a viable solution to address the emerging interconnect bottleneck in data centers and high-performance computing with power efficient and cost effective optical interconnects. Most of the required components such as waveguides or modulators are already available in group IV materials [1,2]. The key missing component for monolithic EPICs is an efficient and CMOS compatible laser source. The major obstacle in this respect is the indirect bandgap nature of group IV semiconductors such as Si and Ge, making them inefficient light emitters that do not yield room temperature stimulated emission. However, despite having an indirect bandgap, Ge has been identified as a possible link between electronic and light-emitting photonic applications. Indeed, the 140 meV difference between the direct (Γ) and indirect (L) conduction band minima can be reduced via strain engineering, resulting in a fundamental direct gap semiconductor. In this context two approaches have yielded encouraging results: epitaxial growth of Ge on larger lattice constant GeSn buffers [3], and micro-processing of uniaxially strained Ge bridges [4].

The latest approach for producing a fundamental direct bandgap in group IV materials is the alloying of Ge with Sn [5]. In this contribution we will discuss the light emission properties of Chemical Vapor Deposition (CVD) - grown GeSn layers with Sn-contents of up to 14% based on photoluminescence (PL) and reflection spectroscopy. Special emphasis is put on the laser emission with different resonator geometries.

2. Band engineering and photoluminescence study

The transition from a fundamental indirect to a fundamental direct bandgap GeSn alloy was shown to occur for cubic crystals (zero strain) at about 8.5 at.% Sn concentration (Fig. 1a) [8]. However, the pseudomorphic growth of GeSn on Ge buffers results in a large compressive strain, on the order of 1.8% for a Sn content of 12 at.%, which pushes the required Sn content to very large values. Fortunately, the direct bandgap transition can be reached for partially relaxed films at Sn contents and residual compressive strain values which are experimentally accessible. Fig. 1a shows the indirect and direct bandgap regions as a function of Sn content and compressive strain in the alloy. Even if the formal direct-indirect transition is reached, for instance for a 50% strain relaxed $Ge_{0.875}Sn_{0.125}$ layer, further relaxation, and thus a larger directness $\Delta E_{\Gamma\text{-}L}$ defined as the energy difference between the Γ- and L- valleys, would be highly beneficial in order to increase the temperature stability of the laser.

Thermal annealing, the most common technique for elastic strain relaxation, is limited for Sn-based systems due to thermal budget constrains due to Sn diffusion. On the other hand, strain relaxation can be obtained by the in-situ epitaxial growth of thick layers exceeding a few 100 nm. Although considerable progress has been made concerning the CVD of GeSn alloys [6, 7], the growth of high quality thick layers is still very challenging. The ability to grow 0.5 µm thick layers was only shown recently, resulting in the demonstration of the fundamental direct bandgap for partially relaxed GeSn alloys with 12.5 at.% Sn [8]. Here we present two approaches to further increase the directness of the alloy, which are i) epitaxial growth of thick and, therefore, highly strain relaxed GeSn layers and ii) increasing the Sn content in the alloys up to 14 at.%.

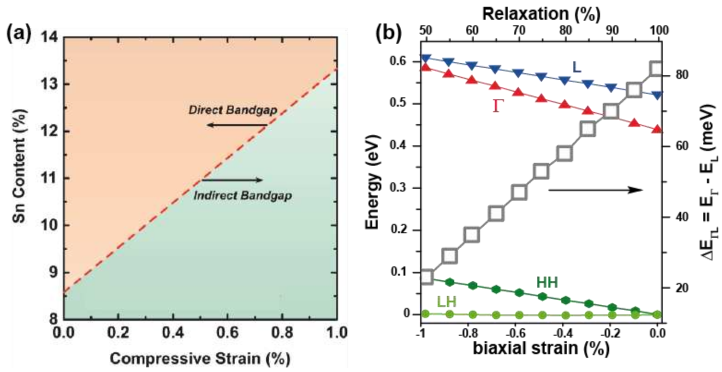

Fig. 1: (a) Experimentally determined indirect to direct transition as a function of Sn content and compressive strain in the layer [8]. (b) Energy levels from band structure calculations (left axis) and directness, $\Delta E_{\Gamma\text{-}L} = E_\Gamma - E_L$ (right axis), for $Ge_{0.875}Sn_{0.125}$ layers as a function of the relaxation degree/residual compressive strain.

Concerning the first approach, band structure calculations for a GeSn alloy with 12.5 at.% Sn concentration, shown in Fig. 1(b), indicate a high directness of about 80 meV in the fully relaxed alloy. This increased energy separation between Γ and L leads to a suppression of Γ- to L-valley carrier transfer which would otherwise reduce the Γ- valley population. As shown in Fig. 1(b), the biaxial strain in the alloy is coupled to its bandgap; therefore, an increased relaxation also translates into a reduction of the bandgap. Room temperature reflection spectroscopy measurements, shown in Fig. 2(a), feature a shift of the absorption band-edge down to about 0.43 eV for a 970 nm thick layer at room temperature. Furthermore, the room temperature PL signal associated with a 970 nm thick GeSn layer is 25 times more intense than that for a 215 nm thick layer of identical alloy composition (e.g. 12.5%).

The second approach for enhancing light emission is to increase the Sn content in the alloy. Low temperature PL measurements performed at 50 K, where nonradioactive recombination via crystal defects are reduced, show the benefit of this approach in Fig. 2(c). A huge PL intensity increase is observed for the higher Sn content alloy (e.g. 14%), although the layer thickness and therefore the strain relaxation are reduced compared to alloys with a lesser Sn content. A similar trend is also seen at room temperature. The strong PL emission from these layers makes them attractive for the fabrication of lasing devices.

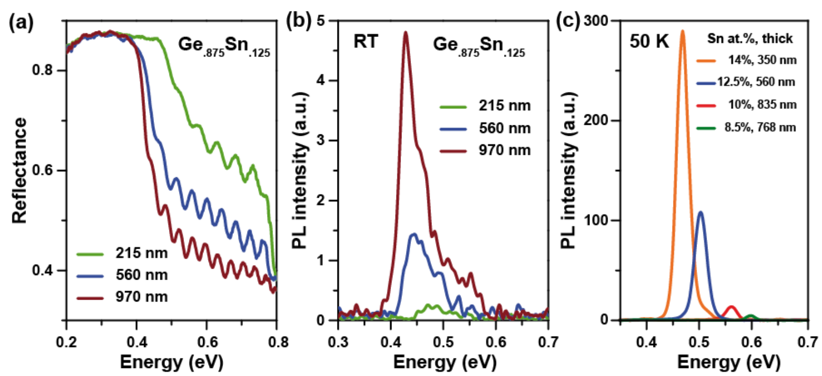

Fig. 2: (a) Reflection and (b) room-temperature photoluminescence (PL) spectroscopy measurements for different thicknesses $Ge_{0.875}Sn_{0.125}$ layers. (c) Low temperature PL for GeSn alloys with different Sn contents.

3. Germanium-tin lasers

Waveguide structures can serve as Fabry-Perot laser cavities and support lasing as recently demonstrated in [8]. They can also serve as waveguide photodetectors in which the long cavity (absorption length) allows the efficient collection of photons [9]. Meanwhile, microdisk type devices are attractive for laser integration with planar Si or Ge based photonics. They indeed provide an integration path without the technological challenges associated with the fabrication of Distributed Bragg Reflector (DBR) mirrors. The heterogeneous integration of III-V microdisk lasers and waveguide detectors with SOI CMOS has been intensely pursued in recent years [10]. The use of GeSn alloys will allow monolithic integration with group IV planar photonics and could even pave a path towards a fully integrated technology combining light generation with the current capabilities of group IV photonics and monolithically integrated electronics.

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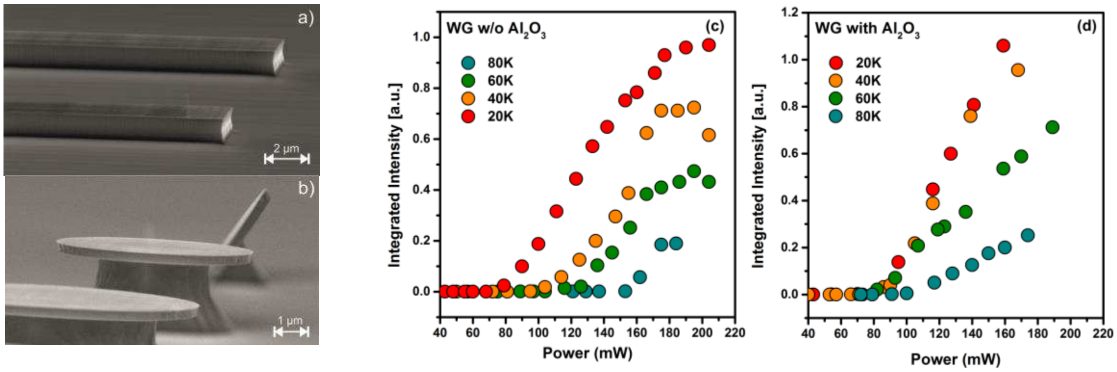

Fig. 3: Scanning Electron Microscopy (SEM) images of GeSn Fabry-Perot (a) and microdisk (b) resonators fabricated with a standard Si technology. (c,d) laser emission of 560 nm thick $Ge_{0.875}Sn_{0.125}$ waveguides grown on Ge buffers on Si substrates, as a function of the excitation power at different temperatures. (c) un-passivated and (d) 10 nm Al_2O_3 passivated structures.

Fabry-Perot and microdisk resonators were fabricated for the study of optically pumped GeSn lasers (see Fig. 3a,b). GeSn layers with thicknesses between 300 and 800 nm and Sn contents between 8.5 at% and 14 at.% were investigated. Lasing at temperatures below 100K was achieved for all resonator geometries by optical pumping with a pulsed Nd:YAG laser (5 ns pulse duration).

For 560 nm thick $Ge_{0.875}Sn_{0.125}$ layers under a compressive strain of about -0.4% modal gain values up to 110 cm^{-1} were measured at T = 20 K and at the photon emission energy of 558 meV via the variable stripe length method (VSL); optically pumped lasing was demonstrated [8]. The gain increases linearly with the excitation intensity, resulting in a differential gain of approx. 0.40 cm/kW and a lasing threshold of 325 kW/cm^2. The emission collected as a function of the excitation intensity from the waveguide facet of a 5 µm wide and 1 mm long $Ge_{0.875}Sn_{0.125}$ Fabry-Perot resonator is displayed in Fig. 3c,d for different temperatures. A clear laser threshold behaviour is observed in the emission intensity at around 70 mW pump power at T = 20 K. The output intensity vs. optical excitation curves for different temperatures gives us the temperature dependence of the lasing threshold. Devices without (Fig. 3c) or with a 10 nm thick Al_2O_3 passivation layer deposited on top of the stripe (Fig. 3d) were compared. Passivation reduces the carrier surface recombination. The lasing threshold is then definitely improved (e.g. reduced) at temperatures above 40K. The temperature dependence of the lasing threshold is also much reduced for passivated devices.

The use of GeSn alloys with a larger directness, as presented above, and the study of the role of interface defects in under-etched and passivated GeSn microdisk resonators will provide important insights towards the fabrication of room temperature, electrically pumped lasers with a fully group IV technology.

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