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Strain-Engineered Group IV Light Sources for Photonic-Integrated Circuits

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ABSTRACT

Integration of photonic devices with CMOS circuits has recently generated much interest for numerous applications ranging from Internet networks to sensor technology. For example, integrated optical interconnects have emerged as a strong contender to replace bandwidth-hungry and energy-guzzling electrical interconnects in data centers and inside microprocessors. However, the lack of group IV semiconductor materials suitable for light emission has thus far prevented the realization of such important photonic-integrated circuits. In this paper, we will present our research works on strain-engineered group IV light sources on silicon that will help enable photonic-integrated circuits.

Keywords: Photonic-integrated circuits, strain engineering, germanium, germanium-tin, silicon photonics, laser, bandstructure engineering

1. MOTIVATION FOR STRAIN-ENGINEERED GROUP IV LIGHT SOURCES

Since the introduction of the first transistor over half a century ago, the advances in device physics and fabrication technology have been enabling transistor scaling to enhance its speed and to increase device packing density in integrated circuits (IC)¹. While this scaling of individual logic elements has made tremendous progress, electrical interconnects for communications between devices started causing the performance degradation of IC². For example, as the scaling of electrical wires as well as increasing complexity of wiring increases the RC time delay, computational speed of IC became limited by interconnects, not by individual devices as predicted 3 decades ago in Figure 1². In addition, energy consumption by electrical interconnects has been constantly increasing with device scaling and is thereby contributing more than 50% of the total dynamic power consumption of microprocessors³.

Figure 1. Prediction in 1982 of time delay of interconnects in different materials and average gate delay versus year.²

While communications within IC became more problematic as technology advances, long-haul communications have been revolutionized by fiber-optic communication systems which transmit information by sending modulated light through an optical fiber. Because optical communications have several advantages over the conventional electrical communications such as low signal attenuation, ability to transmit several channels on a single link, etc., they have been

successfully adapted into systems of smaller scales as shown in Figure 2⁴. As this trend continued, researchers started searching for hope of alleviating the performance bottleneck of IC due to electrical interconnects by employing on-chip optical interconnects⁵.

Figure 2. Optical communication systems at different length scales. ⁴

Figure 3 presents a schematic diagram of an optical interconnection system and shows four main optical devices in the box: laser, modulator, waveguide and photodetector. While conventional interconnects transmit signals directly from one logic device to another via electrical wires, in an optical interconnection system, electrical signals from the logic device are sent to the modulator in order to modulate a continuous-wave (CW) light from the laser into optical signals. The transmitted light via the waveguide can then be detected by the photodetector and converted back to electrical signals⁶.

Figure 3. Schematic diagram of an optical interconnection system.

Such a system that needs both electronic and optical components on a chip requires monolithic integration of each component for cost-effective application. In this regard, the use of germanium (Ge) for building optical components has recently attracted much attention because Ge can be monolithically integrated on silicon (Si). Therefore, researchers have been extensively working on Ge-based optical devices in order to realize monolithically integrated optical interconnects system. While research on other essential optical components such as modulators, waveguides and detectors has shown tremendous progress⁷⁻¹¹, an efficient Ge light source remains particularly challenging due to its indirect band gap. Although Ge's pseudo-direct bandgap allows some conduction electrons to populate the direct Γ -valley and recombine with holes in a radiative way, the fraction of such electrons occupying the direct Γ -valley is extremely low ($<0.01\%$) because of a much smaller density of states for the Γ -valley compared to the slightly lower indirect L-valley¹². This causes a very low light emitting efficiency ($<1\%$)¹². Nevertheless, desired population inversion and optical gain have been theoretically demonstrated in Ge utilizing a combination of heavy n-type doping ($>1 \times 10^{19} \text{ cm}^{-3}$) and residual biaxial tensile strain ($\sim 0.2\%$)¹³. Here, the residual strain lowers the energy difference between the two conduction valleys, while the n-type doping increases the fraction of electrons in the Γ -valley by filling up the L-valley, thereby enhancing the feasibility of population inversion. Based on this concept, researchers successfully demonstrated both optically and electrically pumped Ge lasers¹⁴⁻¹⁶.

These experimental demonstrations have made a big step towards the realization of photonic-integrated circuits (PICs), but there was still plenty of room for the further dramatic improvements of such technologies. For example, the lasing threshold was too high ($\sim 280 \text{ kA cm}^{-2}$) to be used in power-efficient PICs possibly owing to the yet unfavorable Ge's indirect bandgap. Therefore, it was considered crucial to engineer Ge's bandstructure to reduce the energy difference, and if possible, even invert the two conduction valleys to achieve direct bandgap in Ge^{17,18}. Among various approaches, strain engineering and tin (Sn) alloying have shown great promise for modifying bandstructure and enhancing both radiative recombination and optical gain of Ge^{19–21}. In the following section, we introduce our research progress on Ge-based light sources which mainly employ both strain engineering and Sn alloying techniques.

2. RESEARCH PROGRESS ON GERMANIUM-BASED LIGHT SOURCES

Figure 4a shows scanning electron microscopy (SEM) images of our typical strained Ge structure²². This platform employs a Ge layer under a residual biaxial tensile strain, which is created owing to a large thermal expansion mismatch between Si and Ge during epitaxial growth. Figure 4b shows the fabrication process flow. After EBL patterning and dry etching, the underlying oxide layer is removed by wet etching, and as a result, the central Ge bridge is uniaxially strained due to the same mechanism used for strained Si NWs in Ref.²³. By simply varying the geometrical factors such as NW width or length, tensile strain can be fully customized.

Figure 4. (a) SEM images of our typical strained Ge structure. (b) Fabrication process.

Meanwhile, this method is also promising for the introduction of double heterostructure effect within a homogeneous Ge NW. Conventional heterostructures are usually fabricated by stacking multiple layers of different materials, where a narrow bandgap material is sandwiched between two wide bandgap materials. However, the costly and complicated heteroepitaxy process is a huge obstacle for the realization of heterostructures. Our technique avoids such problems of conventional methods but achieves the same heterostructure effect only by modulating spatial strain in Ge NWs²². Figure 5 shows two types of strain-induced heterostructures; one is a strain-induced double heterostructure (s-DH) and another is a strain-induced graded double heterostructure (s-GDH). The corresponding spatial PL maps show that the light emissions can be highly concentrated in active regions (i.e., the created potential wells) arising from the spatially varying strain distributions.

Figure 5. Strain-induced pseudo-heterostructure in Ge nanostructures.

By leveraging the strained Ge platform introduced in figures 4 and 5, we have also demonstrated optically pumped lasing at a threshold density of 3 kW cm^{-2} ²¹. The Ge laser consists of a central Ge nanowire and a couple of distributed Bragg reflectors (DBRs) on stressing pads on both sides of the nanowire, as shown in figure 6a. The DBRs allow achieving a high quality (Q) factor above 1000, and this device geometry enables a variable strain by changing the length of stressing pads. In figure 6b, a highly uniform tensile strain distribution was observed over the flat Ge nanowire with a large optical mode confinement factor of ~ 0.45 . The simulations confirmed that this Ge nanowire could support a fundamental transverse electric (TE) mode at the peak emission wavelength of 1530 nm (figure 6c). With the pump power increased from 0.7 to 3.5 kW cm^{-2} , the PL spectra show a gradual transition from a broad spontaneous emission to lasing oscillation with a superlinear increase of intensity and a linewidth narrowing (figure 6d). It should be noted that the operating temperature was kept at 83 K. At the highest pump power, only the cavity modes around 1530 nm are permitted to enter into the lasing regime with optical net gain while other modes show saturation in intensity. These characteristics provide strong evidence of low threshold lasing in strained Ge nanowires.

Figure 6. Strained Ge nanowire lasers. (a) Schematic view of a Ge nanowire laser containing a strained nanowire gain medium surrounded by a pair of DBRs on the stressing pads. (b) Experimental strain mapping and simulated optical field distribution. (c) Simulated TE mode distribution. (d) Pump-dependent PL spectra of a 1.6%-tensile strained Ge nanowire laser. (e) Integrated PL intensity and linewidth evolution versus optical pump power.

Along with tensile strain, incorporation of Sn atoms into Ge can effectively reduce the energy difference between direct and indirect valleys, and it has demonstrated promising progress in GeSn lasers recently^{19,24}. Pseudomorphic GeSn grown on Ge inevitably suffers from a certain amount of compressive strain which is dependent on the thickness and composition. This compressive strain offsets the positive effects of Sn alloying in Ge in achieving a low-threshold GeSn laser. The large optical mode area is also a limiting factor that roars large power consumption, and makes it difficult for compact photonic-electronic integration. Although a strain-relaxed GeSn microdisk with a small optical mode area has recently been reported²⁵, it showed a small Q-factor (~ 340) with inhibited lasing actions. Here, we demonstrate a hexapole-mode GeSn photonic crystal (PhC) laser structure (figure 7) which can solve all the above-mentioned problems. The built-in compressive strain in the GeSn layer is released by selectively undercutting the underneath Ge layer. This strain relaxation leads to an increased electron population in the Γ valley. In addition, due to the strain distribution in the GeSn slab, charge carriers are expected to accumulate in the strong optical field region, resulting in an improved net gain and lasing-threshold reduction. Additionally, the optical mode area in our laser is smaller than any other reported GeSn cavities, which enables a lower power consumption for lasing. In our simulation, due to strong optical confinement in the 2D PhC structure, a high Q-factor of 9.5×10^4 is obtained. The emission spectra could be tuned in a wide range from 1600 nm to 2200 nm by simply modifying the inner hole-radius.

Figure 7. (a) Structure of the hexapole GeSn PhC cavity. (b) SEM image of the free-standing slab of GeSn cavity. (c) 2D Raman spectroscopy mapping over the cavity region.

3. SUMMARY

In conclusions, we have introduced our recent research progress in Ge-based light sources. We have discussed the motivation of photonic-integrated circuits and Ge-based light sources comprehensively. We have concluded that applying tensile strain and Sn alloying in Ge show great promise for improving the performance of Ge-based on-chip light sources by modifying the bandstructure of Ge towards the direct bandgap effectively. Our technologies may open up the possibility for creating ultra-compact, low-threshold, CMOS-compatible group IV lasers for fully monolithic photonic-integrated circuits.

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