Research article

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Monolithic integrated emitting-detecting configuration based on strained Ge microbridge

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Abstract: The strain technology is accelerating the progress on the CMOS compatible Ge-on-Si laser source. Here, we report a monolithically integrated microbridge-based emitting-detecting configuration, equipped with lateral $p-i-n$ junctions, waveguide and gratings. The operating wavelength range of the emitting bridge and the detecting bridge are matched through the designed same dimensions of the two microbridges, as well as the strain. Strain-enhanced spontaneous emission and the effect of spectra red-shifting on low-loss transmission of on-chip light are discussed. Temperature dependence experiments reveal that in devices with highly strain-enhanced structure, the strain variation can offset the effect of electron thermalization, so that the performance of the device remains stable when temperature changes around room temperature.

Keywords: bandgap engineering; electrical driven; emitting-detecting; Ge microbridge.

1 Introduction

A light source plays an indispensable role in photonic integrated circuits, optical interconnection, optical communication and numerous other optical applications scenarios. With large optical gain originating from their direct bandgap transitions, III–V materials have made

great progress in widely tunable, low noise and narrow linewidth lasers through heterogeneous integration on SOI platform [1–3]. However, an electrically driven group IV laser is still a long-term pursuit in the silicon photonics field for its better CMOS compatibility and financial advantages, which are conducive to mass production. The stumbling block to a silicon laser is the indirect band structure, hindering the optical transitions. Germanium, a group IV material with near direct band structure configuration, whose Γ valley is only 140 meV higher than the L valley, has been proved a good candidate as its directness of the band structure can be improved through bandgap engineering [4–17].

Alloying with Sn [5–10] and uniaxial tensile strain based on microbridge structure [12–16] are two mainstream bandgap engineering methods to achieve Ge lasers. GeSn is an advanced technique, based on which an optically driven continuous wave microdisk laser was reported, with well-designed thermal management and SiN_x layer to introduce extra biaxial tensile strain to increase the directness [6]. Besides, microbridge has been used for Ge lasing and been demonstrated to be compatible with GeSn system [4]. The strain threshold for Ge to become a direct band gap material is 6% for uniaxial tensile strain and 2.1% for biaxial tensile strain at room temperature [12]. The thermal stress in the epitaxial Ge layer directly grown on Si will result in an in-plane biaxial tensile strain of $\sim 0.16\%$ [18], which can be amplified by a microbridge structure to biaxial tensile of $\sim 2\%$ [18] or uniaxial tensile strain of more than 5% [19]. Despite these results being crucial advancements for the research of group IV lasers, they are still at the level of optically-driven. On the other hand, a waveguide type resonant cavity, which not only has a resonance enhancement effect on the emission light, but also has a guiding effect to make it convenient to conduct light signals to other monolithically integrated photonic components, is still inexistent, especially in the microbridge structure.

A series of theoretical studies on electrically driven Ge microbridge lasers have been carried out before.

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The theoretical models for strained band structures and optical gain are given by the eight band k - p method [20]. Further, a CMOS-compatible Distributed Bragg Reflector (DBR) Ge laser was designed, including high uniaxial tensile strain, low loss optical resonator and heterojunction for electrical injection. The simulation results predicted that the limitation of the threshold current density and internal quantum efficiency are 29 kA/cm^2 and 19.6% [21]. Besides, uniaxially tensile stressed bulk Ge and Ge/SiGe quantum well were compared, indicating that the strained bulk Ge is a better platform for a Si-compatible light source [22].

Experimentally, a lateral p - i - n junction has been successfully implemented in a strained Ge microbridge, with p -region and n -region located on the strain-free pad and the strained microbridge area serving as the i -region, to achieve the enhanced electroluminescence [13]. In this paper, we introduce a waveguide, a DBR grating resonator and a coupling grating on the basis of the previous electrical design. The p -region and the n -region are moved to the strained area, located on both sides of the waveguide. The previous design can produce pseudo-heterostructure effect to improve the carrier injection efficiency. However, the current p - i - n structure can make space for the waveguide and the DBR gratings, and keep the waveguide away for the high loss doping area.

In addition, an emitting-detecting configuration is established exploiting a pair of cascaded microbridges with one lateral p - i - n junction forward biased and the other reverse biased. Raman spectroscopy indicates that $\langle 100 \rangle$ uniaxial tensile strain of 2.6% is introduced into both microbridge regions, making the reverse biased bridge have the same band structure with the emitting bridge, which matches their operating wavelength ranges. We argue that—for our case—the strain-induced spectra red-shifting effect makes strained Ge active devices operate in the low-loss window of waveguide made of as-grown Ge,

which is conducive to the monolithic integration on the Ge-on-Si platform. Temperature dependency of the device performance is also explored. In microbridge structure with weak strain enhancement (uniaxial tensile strain of 1.6% at 300 K), the electron thermalization will facilitate the spontaneous emission. However, in a strong strain enhancement case (uniaxial tensile strain of 2.6% at 300 K), the strain reduction with increasing temperature will counteract the effect of thermalized electrons, keeping the electron statistics in Γ valley stable, as well as the spontaneous emission.

2 Device design and fabrication

The double strained-microbridge cascaded emitting-detecting configuration is schematically shown in Figure 1(a). A pair of microbridges are implemented in our device, one serves as the emitter and the other acts as the detector. For each microbridge, wider pads are connected to both sides for suspending. With such a structure, the thermal stress in the Ge layer can be concentrated into the microbridge, leading to a uniaxial tensile strain to enhance the band structure directness. The structural parameters of the two microbridges are kept consistent to ensure that the band structure of the detecting Ge matches the emitting Ge, creating a detector whose response wavelength covers the emitter wavelength. Along the direction of microbridges is a ridge waveguide with a surface DBR grating on it, which forms a resonant cavity with a focusing DBR grating. At the end of the waveguide, a grating coupler is etched out. The dimensions of the gratings are optimized to align spectra with the spontaneous emission peak wavelength from a strained Ge microbridge.

Figure 2(a)–(c) show the schematics of the side and top view of the focusing DBR grating, the grating coupler and the surface DBR grating. Dimension parameters are

Figure 1: (a) Schematic of the double strained-microbridge cascaded emitting-detecting configuration (not to scale). (b) Sectional view of the suspended Ge microbridge. (c) Fundamental TE mode profile.

optimized with finite difference time domain (FDTD) method. As illustrated in Figure 2(d), coupling efficiency of the grating coupler and reflection spectrums of the two DBR gratings are optimized to match the electroluminescence of a Ge microbridge with uniaxial tensile strain of 1.76%. The wavelength of the reflection peak of the surface grating is consistent with the electroluminescence maximum, locating at $1.85\ \mu\text{m}$, where the grating coupler has an efficiency of 20%. Additionally, the focusing grating has a flat reflection spectrum over a wide range of wavelength, which is easy for a narrow surface grating reflection spectrum to align with, improving the fabrication robust [22].

As depicted in Figure 1(b), the p -regions and n -regions of the p - i - n junctions on the emitting and detecting microbridges are located on both sides of the waveguide, connecting with electrodes for current injection. The fundamental TE mode profile, simulated with finite element method (FEM), is presented in Figure 1(c).

As shown in Figure 3, a two-step growth technique is adopted in the Ge layer epitaxy for high crystal quality and uniform tensile strain distribution. First, a buffer layer is deposited at $400\ ^\circ\text{C}$, followed by the high-quality layer epitaxy at $600\ ^\circ\text{C}$. Subsequent annealing is carried out to reduce the threading dislocation density. Then the first step is repeated so that the thickness of Ge layer reaches $1\ \mu\text{m}$.

Figure 2: Schematics of gratings and the corresponding characteristics.

(a) Ocusing DBR grating. (b) Grating coupler. (c) Surface DBR grating. Dimension parameters are marked. (d) Coupling efficiency of grating coupler, reflection of focusing grating and surface grating and their alignment with the EL spectrum of a Ge microbridge of 1.76% uniaxial tensile strain [13].

According to Ref. [23], an additional buffer layer grown at low temperature can reduce the surface roughness. The measured threading dislocation density is $\sim 2 \times 10^7 \text{ cm}^{-2}$ [13].

Figure 4 depicts the fabrication flow of the double strained-microbridge emitting-detecting configuration. First, microbridges, waveguide and gratings are patterned successively with UV lithography, electron beam lithography (EBL) and inductively coupled plasma (ICP) etching. Second, BF_2^+ and P^+ implantations are performed to construct the lateral $p-i-n$ junctions (see Supplementary material for implantation parameters). Rapid thermal annealing of 1 min is carried out in a N_2 atmosphere at 650°C for dopants activation and lattice damage repair. A SiO_x protection layer is deposited before the annealing to prevent dopants out-diffusion. To establish the electrode contact, windows are opened on the insulating layer in advance with UV lithography and buffered oxide etchant (BOE). During the contact windows patterning, Shipley

S1805—a photoresist resistant to BOE corrosion—serves as the mask. After that, the electrode patterning is performed, followed by the electron beam evaporation of 20 nm Cr/90 nm Au and the standard lift-off process. Finally, the underlying Si substrate is removed with tetramethylammonium hydroxide (TMAH) solution to suspend the Ge microbridges. In this process, it should be noticed that the metal electrodes have to be covered to prevent the Ge microbridges from being etched by a metal-Ge-TMAH electrochemical cell [13]. A 120 nm SiO_x layer is deposited and the wet etching windows are opened with BOE. The subsequent Si wet etching is performed in a 5% TMAH solution at 73°C . After removing the oxide layer covering the surface, the electrode is exposed for the convenience of the test with probes. The scanning electron microscope (SEM) images of the fabricated device is shown in Figure 5(a), with emitting and detecting microbridges marked. Figure 5(b), (c), and (d) are the magnified view of the focusing DBR grating, grating coupler and surface DBR grating on the ridge waveguide, respectively.

Figure 3: Schematic of the Ge-on-SOI epitaxy process flow.

3 Characterization of the lateral $p-i-n$ junction and strained Ge

3.1 Measurement of the current–voltage dependency

Carriers are injected into the active area—highly strained Ge microbridge—by a lateral $p-i-n$ junction with a length of $10 \mu\text{m}$ and a width of $5 \mu\text{m}$. Figure 6(a) is the current and

Figure 4: A simplified fabrication flow of the double strained-microbridge cascaded emitting-detecting configuration.

Figure 5: Scanning electron microscope (SEM) images of the fabricated device.

(a) Overall view of the emitting-detecting configuration with both of the microbridges suspended. (b) Focusing DBR grating. (c) Grating coupler. (d) Ridge waveguide with surface DBR grating.

the corresponding current density of the junction as a function of the voltage in the range of -0.3 to 0.5 V. The current-voltage characteristics are measured with a Keithley 2401 source meter equipped with a pair of probes. The inset shows the semi log current density–voltage relationship, from where an on–off ratio of 100 can be extracted. The series resistance and the ideality factor are extracted by fitting the current density–voltage characteristics with the following diode model:

$$J = J_s \left[\exp \left(\frac{q(V - JAR_s)}{\eta k_B T_k} \right) - 1 \right] \quad (1)$$

where J_s is the reverse saturation current density, A is the junction cross section area, R_s is the series resistance, η is the ideality factor, q is the electron charge, k_B is the Boltzmann constant and T_k is the temperature. The device exhibits a fitting reverse saturation current density of 2.145 A/cm^2 . The calculated series resistance R_s is 189Ω and the ideality factor η is 2.2. Figure 6(b) presents the carrier

distribution simulated by finite element method (FEM), in which the injected electrons are uniformly confined in the i-Ge region. The calculated average injected carrier density in the waveguide area is depicted in Figure 6(c). For a current density of 4 kA/cm^2 under a forward bias voltage of 0.5 V , the injected carrier density can reach to $4 \times 10^{17} \text{ cm}^{-3}$.

3.2 X-ray diffraction and Raman spectroscopy

X-ray diffraction (XRD) and Raman spectroscopy are performed to characterize the strain status in the Ge material according to the corresponding relationships between locations of the diffraction peak and Raman peak and the strain value [24]. A 532 nm laser source is used in the Raman test, focusing by a 100× object to the sample surface with a spot size of $0.8 \mu\text{m}$. To eliminate the heating effect on the Raman shift, the laser power is reduced to 0.5 mW with an

Figure 6: Current–voltage dependency and the calculated injected carrier density for a lateral p – i – n junction with a length of 10 μm . (a) Dependency of the injected current and the related current density on the voltage. The inset is the semi log current density–voltage relation. (b) Distribution of the injected carrier density with injected current density of 4 kA/cm^2 . (c) The calculated injected carrier density as a function of the current density.

attenuator. The full width at half maximum (FWHM) of Ge layer is 0.0817° , larger than the result of 0.0338° (121.7 arcsec) in Ref. [25]. But comparing with the Si peak FWHM of 0.0161° , the crystal quality of Ge layer is still acceptable. The marked Ge peak locates at $2\theta = 66.107^\circ$, from which a biaxial tensile strain of 0.21% is derived, corresponding to a Raman shift of 0.9 cm^{-1} relative to the relaxed Ge. Relative Raman shifts for the two Ge microbridges with different wet etching time of 15 and 20 min are 2.6 and 4.3 cm^{-1} , representing for uniaxial tensile strains of 1.6 and 2.6%. See

Supplementary material for the X-ray rocking curve and Raman spectra, as well as the strain calculating method.

4 Experiments and discussion

4.1 Comparison between highly strained and unsuspended devices

The detecting p – i – n junction is reversely biased with a voltage of 0.2 V. A lock-in amplifier scheme is adopted in the experiments to eliminate the influence of ambient light. As presented in Figure 7, the emitting part is powered by a function signal generator with a 1 kHz square wave excitation signal. The duty cycle is tuned to 20% to reduce the average output power to protect the device under test (DUT). The detecting part is reversely biased by a digital source meter at the voltage of 0.2 V. A resistance of 50 Ω is employed in the circuit to convert the photocurrent into a voltage signal. Since the photocurrent is on the order of microamperes, the reverse bias voltage fluctuation at the detecting end caused by the voltage change at both ends of the resistance is negligible. The signal generated at the detecting end is extracted from the noise by phase-sensitive detection with the lock-in amplifier. The DUT is placed on a thermo electric cooler (TEC) to adjust its temperature.

Tuning the injected current density of the emitting part at the range of 0–0.35 kA/cm^2 , the output from the detecting part denoised by the lock-in amplifier for the suspended and unsuspended devices are recorded, presenting in Figure 8 in logarithmic ordinate. Whether in an unsuspended or suspended device, the band structures of the detector and emitter material can always match with each other, causing the detector to efficiently convert the emitting light signals into current. With the enhancement of the light emission, the output current of the detecting microbridge also gradually increases.

The output of the device with uniaxial tensile strain of 2.6% is 36 times larger than that of the device unsuspended ($\epsilon_0 = 0.21\%$). To analyze the enhancement factor, band structure is simulated with the eight band k – p method, which is detailed in Ref. [13], and spontaneous emission rates and absorption coefficients are calculated with the joint density of state (JDOS) model (see Supplementary material for calculation method), comparing with the experimental data in Ref. [26].

On one hand, the improved directness of the material band structure due to the strain contributes to the spontaneous emission of the emitting part. The strain-dependent band structure evolution of Ge leads to a

Figure 7: Schematic of the experimental set-up, highlighting the main elements: Lock-in amplifier, function signal generator, digital source meter, resistance of 50 Ω , device with emitting-detecting configuration under test on the thermo electric cooler (TEC).

Figure 8: Comparison of the output from the detecting microbridge between the suspended device with $\epsilon_x = 2.6\%$ and the unsuspended device with a reverse bias voltage of 0.2 V on the detecting $p-i-n$ junction, at room temperature. For the current density of 0.3 kA/cm² at the emitting part, the injected carrier density is $4.6 \times 10^{16} \text{ cm}^{-3}$.

reducing difference between the direct bandgap at Γ point and the indirect bandgap at L point, which will increase the electron population in the Γ valley, resulting in the spontaneous emission enhancement. As elaborated in the Supplementary material, under the injected carrier density of $4.6 \times 10^{16} \text{ cm}^{-3}$, the integrated spontaneous emission rate for $\epsilon_x = 2.6\%$ is $3.0 \times 10^{21} \text{ cm}^{-3} \text{ s}^{-1}$, 7.3 times larger than that of the situation $\epsilon_0 = 0.21\%$ ($r_{\text{int}} = 4.1 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}$).

On the other hand, the strain-induced spectra red-shift is responsible for the extra enhancement of the detecting output (see Supplementary material). The increasing strain

will lead to the shrinkage of the bandgap of the material. For the case of $\epsilon_0 = 0.21\%$ —the biaxial tensile strain in the unsuspended microbridge and the connecting waveguide, the emission peak locates at $1.57 \mu\text{m}$, in the range of the waveguide absorption wavelength of $<1.62 \mu\text{m}$, which causes great loss propagating to the detecting microbridge. However, as uniaxial tensile strain of 2.6% introduced into the microbridges, the direct bandgap at Γ point becomes 0.6 eV, corresponding to the spontaneous emission peak at $2.05 \mu\text{m}$, matching with absorption edge at $2.1 \mu\text{m}$. The spontaneous emission spectrum is beyond the absorption range of the Ge waveguide, leading to a much smaller propagation loss than the unsuspended case.

4.2 Exploration on the temperature-dependency of the device performance

The experimental results of the detecting output as function of injected carrier density at different temperatures for devices with uniaxial tensile strain of 1.6 and 2.6% at room temperature are presented in Figure 9(a) and (b). The output of the detecting microbridge increases linearly with the current injected into the emitting microbridges.

Due to the strain varies with the changing temperature, the strain status of the microbridge can be described by an enhancement factor ϵ_x/ϵ_0 for convenience (see Supplementary material), which are 7.6 and 12.4, respectively. For a pair of microbridges with $\epsilon_x/\epsilon_0 = 7.6$, the detecting output increases with the accumulating temperature, as shown in Figure 9(a), while keeping consistent for the case of $\epsilon_x/\epsilon_0 = 12.4$ illustrated in Figure 9(b).

Figure 9: Comparison of the detecting output variation tendency with changing temperature for different strain values and the corresponding analysis.

(a) Detecting output for a microbridge of $\varepsilon_x/\varepsilon_0 = 7.6$ at different temperatures. (b) Detecting output for a microbridge of $\varepsilon_x/\varepsilon_0 = 12.4$ at different temperatures. (c) Schematics of the electron thermalization with increasing temperature. (d) Electron statistics variations with temperature for Ge microbridges of $\varepsilon_x/\varepsilon_0 = 7.6$ and $\varepsilon_x/\varepsilon_0 = 12.4$.

There are two mechanisms that affect the temperature characteristics of the device. First, as illustrated in Figure 9(c), a rising temperature promotes electrons from lower states in L valley to the Γ valley due to the effect of thermally broadened Fermi distribution [9]. But from the perspective of the strain properties of the Ge microbridge structure, the thermal stress in the material will reduce with increasing temperature, as well as the concentrated uniaxial tensile strain in the bridge region [12], which is shown in Supplementary material, simulated with the finite element method according to thermal expansion coefficients of Si [27, 28] and Ge [28]. So, the directness of the band structure is weakened, leading to less population of electron in the Γ valley. The electron population is calculated by integrating the product of the density of states in the conduction band and the Fermi–Dirac function (see Supplementary material).

For a weakly strain enhanced structure with $\varepsilon_x/\varepsilon_0 = 7.6$, there is little strain variation. Thus, the electron thermalization dominates the performance of the device, as shown in Figure 9(d), which facilitates the spontaneous emission.

In a highly strain structure with $\varepsilon_x/\varepsilon_0 = 12.4$, the effect considerable strain variation is able to offset the thermalized electrons, as illustrated by the green line in Figure 9(d), forming an electron statistics equilibrium around the room temperature.

4.3 Characterization of the emission efficiency and responsivity

To calculate the efficiency of the emitting microbridge and the responsivity of the detecting microbridge, electroluminescence (EL) test of the unsuspended device is also performed using the set-up shown in Figure 10(a). The system is still based on a lock-in amplifier, with a function signal generator powering the emitting part with a 1 kHz square wave signal. An object is placed above the grating coupler for the light collection. The light beam is focused on an InGaAs detector to convert optical signals into electrical signals. The electrical signals are sent to the lock-in amplifier and then output to the computer. The detector is fixed on

Figure 10: (a) Schematic of the electroluminescence test set-up used in this work. (b) EL test result of the unsuspended device.

a flip frame and can be easily flipped down to move out of the light path for the chip observation with a CCD.

Figure 10(b) depicts the InGaAs detector output as a function of the injected current density, showing a linear growth trend. The injected current density was increased to a high level to enhance the light emission, compensating the low efficiency of the grating coupler. Such test was only performed on the unsuspended device. For the suspended device with high strain, large current injection can easily destroy the $p-i-n$ diode due to the poor heat dissipation.

The emission efficiency can be derived from the above EL test results, the theoretical spontaneous emission spectrum and the transmission function of the test system (see Supplementary material for calculation methods). The calculated emission efficiency of the unsuspended emitting microbridge with biaxial tensile strain of 0.21% is 0.48%. For the suspended device with uniaxial tensile strain of 2.6%, the integrated spontaneous emission rate is 7.3 times larger than the unsuspended case, so the emission efficiency is 3.50%.

After calibrating the emission intensity of the emitting diode, the responsivity of the detecting microbridge diode can be determined according to results of the on-chip emitting-detecting experiment (see Supplementary material). The peak wavelength responsivities of microbridges with biaxial tensile strain of 0.21% and uniaxial tensile strain of 2.6% are 0.8 and 1.0 A/W, respectively.

In order to evaluate the calculation, the results are compared with data in literature. The simulation results of emission efficiency with strain value, injected carriers density and n -type doping concentration of the active region are given in Ref. [29]. The emission efficiency is 3%

when the n -type doping concentration of the active region is $5 \times 10^{18} \text{ cm}^{-3}$, the injected carrier density is $1 \times 10^{18} \text{ cm}^{-3}$ and the uniaxial tensile strain is 2.6%. In this work, the emission efficiency is higher because the SRH lifetime is longer with the intrinsic Ge material as the active region.

In Ref. [30], the results of responsivity for some waveguide-coupled Ge-on-Si detector are summarized, varying in the range of 0.85–1.1 A/W, which are very close to the estimated values in this work.

5 Conclusions

In summary, we have demonstrated the integration of highly strained Ge light emitter and detector based on microbridge structure. With the well-designed process flow, the emitting part and the detecting part share the same strain value, leading to a match between the absorption and emission spectra. In addition, the strain will not only enhance the spontaneous emission, but also bring about the spectrum red-shifting effect, making the device operation wavelength beyond the absorption range of the waveguide made of as-grown Ge, which is advantageous for propagation of the on-chip light. The temperature dependency is also researched. In a weakly strained device, the electron thermalization will facilitate the spontaneous emission, while the reducing strain with increasing temperature will counteract its effect in highly strained one. Through appropriate strain management, devices with low-loss and temperature stability can be achieved. Such an emitting-detecting configuration has many applications, in which the most obvious one is monitoring the working status of the on-chip light source. Besides, by

combining with other photonic devices like modulators, switches, multiplexers and demultiplexers, etc., photonic integrated circuits (PICs) for photon-based on-chip signal processing and transmission on the Ge-on-Si platform will be realized.

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