Emission wavelength tuning by mechanical stressing of GaAs/Ge/Si microbeams

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Abstract: We propose an approach for tuning a gain spectrum of semiconductor lasers under temperature fluctuations, where the heat-induced effect is dynamically compensated using a mechanical stressing. By stressing GaAs/Ge/Si microbeams, emission wavelength tuning is experimentally demonstrated for the overlying GaAs layers as a proof-of-concept, and the results are followed by theoretical calculations. It is discussed that this approach is effective to cancel the gain spectrum shift and will be indispensable to the integration of light sources toward WDM systems on a chip.

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References and links
1. Introduction

Electronic-photonic convergence based on Si integrated photonics is a viable solution to boost downscaling in Si electronics, and is considered to have the potential for lowering the cost, size and power consumption as well as for enhancing the bandwidth using on-chip wavelength division multiplexing (WDM) [1,2]. Integrated photonic components are diverse, and especially the integration of lasers on Si has been regarded as being the most difficult. Recently, electrically pumped III-V laser bonded on a Si waveguide [3] and optically pumped $n^+$-doped tensile strained Ge-on-Si laser [4] have been demonstrated as candidates of on-chip light sources. However such on-chip lasers would suffer from inevitable heat penalty within 20–80°C ($\Delta T = 60°C$) during the chip operation [5]. The temperature increase causes the band gap shrinkage, leading an emission wavelength change. In particular, conventional InP-based lasers operating in the C+L band (1530–1625nm) used in optical communication suffer from the gain peak shifts at 0.5nm/°C, which is larger than the resonant wavelength shift at 0.1nm/°C [6,7]. Thus it is obvious that the temperature stability will be a crucial issue for the integration of light sources especially in dense WDM (DWDM), where the channel spacing is only 0.8nm (100GHz). The use of Peltier thermo-electric coolers is not suitable for high-density on-chip integration. In order to guarantee reliable communications on a chip, it is necessary to incorporate a method to lock the gain spectrum against the temperature fluctuations.

We are focusing that the strain in a semiconductor material modifies the band edge energies. Recently, our group has proposed a novel platform of Si microbeams to induce a mechanical strain in the overlying material via an elastic deformation, where the mechanical strain is used to control the band gap [8]. Tuning the band gap via stressing is supposed to be applicable for tuning the gain spectrum since the gain appears above the gap.

In this paper, a method to tune the gain spectrum is proposed and its feasibility is discussed. Stress-induced effects on the band gap and the refractive index are theoretically calculated for strained GaAs, as a typical direct-gap semiconductor. The GaAs/Ge/Si microbeams are fabricated, and tuning the band gap is experimentally demonstrated under the mechanical stressing of GaAs layers in $\mu$-PL measurement.

2. Method and theoretical feasibility

The concept in this method is inducing a mechanical stress and tuning the band gap. Elastically strained semiconductor materials exhibit dynamical changes in the electrical/optical properties
of semiconductors. A freestanding microbeam structure [8] is the platform proper to dynamically tune the stress and induce a strain as large as 1% without a mechanical breakdown. In contrast to the conventional strain engineering utilizing the lattice mismatch in heteroepitaxy, the mechanical stress externally applied through a bent microbeam is effective for dynamical tuning regime. The schematic of the bent microbeam is depicted in Figure 1. By controlling the bending, the amount of the mechanical stress can be flexibly controlled. In practical terms, the microbeams are tensile pre-strained at certain temperature, say room temperature, and then its tensile stress is released so that the heat-induced band gap shrinkage is compensated as the temperature increase, since tensile strain and increase in temperature both decrease band gap. The mechanical loading used for stressing will be replaced with a piezoelectricity or an electrostatic force developed in Si MEMS technology. Moreover the Si MEMS technology will enable a fine-tuning with a MHz dynamic response, being effective for precise control of the stress and compensation for temperature fluctuation.

To investigate the feasibility of this method, GaAs is chosen for the model of calculation and experiments. Admittedly GaAs does not emit the light for optical communication band around 1.55 μm-wavelengths. The material of choice here is GaAs, since it is a typical direct-gap semiconductor and its material constants are well known and the results should be a proof-of-concept for various materials application.

In order to estimate the strain effect on the gain spectrum, the changes in band gap are calculated for GaAs as a function of uniaxial [100] strain. The theory used is the deformation potential theory [10]. The elastic constants and the deformation potentials of GaAs are taken from [11,12]. Figure 2 shows the calculated band gap energies. Under uniaxial [100] tensile strain, the conduction band edge in Γ valley is lowered in energy, while splitting occurs for light-hole (lh) and heavy-hole (hh) valence band edges, causing the lh valence band edge is located higher in energy under the tensile stress. This leads to the reduction of the band gap energy, and the minimum band gap is determined by the Γ-lh energy difference. For example, under the uniaxial tensile stress of 1 GPa which corresponds to the strain in +1.17%, the band gap is reduced from 1.42 eV (unstrained) to 1.36 eV (tensile), corresponding to the wavelength change from 873 nm to 912 nm, meaning the dynamic tunability of the gain spectrum of GaAs. It is typically reported that the gain peak is red-shifted with temperature elevation by amount of 0.5 nm/°C in conventional InP-based lasers operating in the C+L band [6]. Since the amount of
the temperature-induced band gap shrinkage is typically comparable in energy scale for most of the semiconductor materials, the gain peak should be similarly shifted as in energy scale. Within the fluctuation of $\Delta T = 60^\circ C$, it will be shifted in 30nm, corresponding to 15 meV around the band gap energy of InP-based laser (0.8 eV). Therefore the requisite tensile strain to cause the energy shift of 15 meV is 0.26% for GaAs (1.42 eV), given that the gain peak energy changes the same amount as the band gap changes and the $\Gamma$-lh transition under the tensile strain is assumed.

3. Experimental procedure

3.1. GaAs epitaxy on Si

Freestanding GaAs/Ge/Si microbeam structures were fabricated by using GaAs epilayers on Ge on silicon-on-insulator (SOI) substrates. The GaAs layers on Ge/SOI were obtained by an epitaxial method. Since high-quality GaAs has been found difficult to grow directly on Si [13], thin Ge epitaxial layers were used as a buffer layer inserted to obtain the low threading-dislocation density in GaAs layers [14,15]. This is because high-quality Ge layers can be grown in spite of 4% lattice mismatch [16], while there is almost no lattice mismatch in GaAs and Ge. A two-step ultra-high vacuum chemical vapor deposition (UHV-CVD) growth was performed for the Ge epilayers (about 100nm) on SOI. The GaAs (about 400nm) was grown by reduced-pressure metalorganic CVD (MOCVD) at 550–650$^\circ C$. Vicinal (001) SOI wafers (top Si: 250nm, BOX: 1.51 $\mu$m) misoriented by 4° toward [110] direction were used to ensure that the GaAs epilayers grown on Ge/SOI structures be free from anti-phase boundary (APB) defects, which is due to polar/nonpolar epitaxy. The GaAs epilayers were successfully obtained without APB, being measured in atomic force microscopy (AFM).

3.2. Fabrication of GaAs layers on Si microbeam

The GaAs/Ge/SOI structures were then processed to fabricate freestanding microbeam structures. Using electron-beam lithography (EBL), followed by a wet under-etching of BOX layer, the microbeams of GaAs/Ge/Si were obtained, having the typical size of 5 $\mu$m in width, 15 $\mu$m
Fig. 3. SEM image of a typical GaAs/Ge/Si microbeam. The microbeams showed a spontaneous upbending after fabrication. Laser microscopic measurement confirmed that the amount of the bending was about 2.5μm in height at the beam end. The upbending deformation is deduced from the relaxation of the built-in strain accumulated during cooling process in the growth chamber to room temperature due to the thermal expansion mismatch between GaAs and Si [17,18].

in length and about 0.75μm in total membrane thickness. Figure 3 depicts the bird-eye view of scanning electron microscopy (SEM) image for the freestanding GaAs/Ge/Si microbeam.

3.3. PL measurement of the microbeam under stressing

μ-PL spectra were measured for the obtained GaAs/Ge/Si microbeams at room temperature. A mechanical force was applied by using a tip with its radius of about 2μm to push the microbeam’s end downward to the Si substrate. The optically pumping area was a circle of about 1μm in radius and is marked in Figure 1. The irradiated power was set to be 0.18mW, which is low enough to ignore the heat production by laser excitation. Although the penetration depth of the pumping laser for GaAs is about 50nm, photogenerated carriers should diffuse in-plane and also out-of-plane to cause ambiguity in the analysis of the PL spectra. The PL signals were measured using the μ-PL system with a liquid-nitrogen-cooled InGaAs array photodetector.

4. Experimental results

The PL spectra from the microbeams are plotted in Figure 4. The spectrum shown in blue is measured without stressing. The peak from this spectrum was identical to a GaAs homoepitaxial layer. The spectrum in red is under stressing. This shows a clear red shift ~ 15meV. The full width at half maximum (FWHM) of the spectrum has shown a slight increase from 43 to 47meV. We will come back this point later on. The spectrum shown in green was measured after removing the tip. Clearly the green spectrum restores the original (blue), indicating that the deformation of the microbeams is elastic. This enables us to conclude that the observed red shift of the peak should be induced by band gap narrowing due to the strain via mechanical stressing, not by other effects such as luminescence from plastic-deformation-induced defects. The elastic deformation also allows us to simulate the strain amount and distribution in the microbeams as shown next.

According to our calculations based on finite element method (FEM), the uniaxial strain around the pumping area was estimated to be deviated in 0.2–0.30% as in Figure 1. The observed red shift of 15meV, therefore, well corresponds to +0.26% strain for Γ-lh transition as in Figure 2. However, it should be noted here that the photogenerated carriers should diffuse prior to their recombination, indicating the PL peaks should not directly correspond to the laser-excited position. It should also be considered that the diffusion of the photogenerated carriers is uphill diffusion in-plane and out-of-plane because the excited region is the lowest in energy.
due to the highest tensile strain. This should reduce the diffusion length of the photogenerated carriers. It is therefore fair to conclude that the PL red shift, i.e., the band gap shrinkage would consist of various band gaps from and near the excited region of the strained microbeam. It is also indicated that we could lock the gain spectrum unchanged against thermal fluctuation on a Si chip ($\Delta T = 60^\circ$C). The speed of stressing can be as quick as the order of MHz, while temperature fluctuation should be much slower than that say $\sim 10$Hz. Therefore, the present results clearly demonstrate that stressing of microbeams is an enabler of locking a gain spectrum on an uncooled chip.

As for the FWHM increase under stressing observed in Figure 4, there are at least two possible reasons, i.e., (1) valence band splitting in terms of the strain and (2) in plane as well as out-of-plane strain distribution of the microbeam. We have already explained both possibilities briefly in above. The first possibility is due to that the strain introduces non-degeneracy in valence band into lh and hh bands, resulting in increase of FWHM. It is less likely to observe such two-separated spectra at room temperature. The second possibility is due to that the strain distributed in the bent microbeam allows various emissions, leading the increase in FWHM. It is not yet clear which dominates the FWHM increase.

5. Discussion

We have studied the effect of strain on GaAs band gap to lock gain spectrum, and demonstrated that locking can be achieved by stressing the microbeam using GaAs/Ge/Si microbeam as a proof-of-concept. The remaining issue is that temperature as well as strain modifies the refractive index in the structure at the same time. For examples, the thermo-optic (TO) coefficient of GaAs around the energy gap ($E_g = 1.42$eV) is $dn/dT = +3 \times 10^{-4}$/°C, thus the index will be changed in $\Delta n = +1.8 \times 10^{-2}$ for $\Delta T = 60^\circ$C. On the other hand, the strain of $+0.26\%$ increases the index in $\Delta n = +0.41 \times 10^{-2}$ according to photoelastic effect. In practical use, the TO effects can be compensated to some extent by releasing the tensile strain but not entirely. Thus, we should introduce another way to completely suppress the wavelength fluctuation. One
way is to utilize the materials having negative TO coefficient as a cladding to athermalize the effective index \(\frac{dn}{dT}\) reported elsewhere [19,20]. Especially in the case of the media having extended gain spectrum under high current injection, this approach can be applied to modulate the index of the guiding media to lock the resonant mode.

Concerning the strain estimation, we have designed the FEM simulation neglecting the effect of microbeam’s upbending which is depicted in the figure 3. If one takes into account the effect of the upbending, the microbeam would be more tensile-strained than shown in the figure 1. This might lead the conclusion that the shift of emission peak is ascribed to both of \(\Gamma\)-lh and \(\Gamma\)-hh transition, not just by \(\Gamma\)-lh band gap minimum. But it is not realistic to reproduce what was happening with the microbeam upbending in the simulation because of the difficulty to fully comprehend PL spectra from stressed GaAs layer. However, regardless of PL analysis, the thing we can say is that the emission spectrum of GaAs layer in the microbeam is red-shifted by applying some amount of tensile stress. The shifting of the emission peak surely indicates that the gain peak would be shifted in a similar analogy.

Finally it is marked that the uniaxial tensile stress along the [100] direction increases the refractive index of GaAs in \(\frac{dn_{zz}}{d\sigma}\) (GPa) = +1.8 \times 10^{-2} along the stress direction and \(\frac{dn_{yy,zz}}{d\sigma}\) (GPa) = +1.1 \times 10^{-2}. Thus GaAs becomes an anisotropic medium in the uniaxial strained region. This phenomenon is known to cause a waveguide birefringence, resulting in different propagation constants of TE and TM modes. P. Kirby et al. [21] analyzed the photoelastic effect on uniaxially strained GaAs/AlGaAs double heterojunction lasers and observed anomalous \(L-I\) characteristics, where the output intensity of TE mode is dominant for TM mode. Further investigations will be necessary to widely use the presented method to lock the emission wavelength on an uncooled chip.

6. Conclusion

We have proposed the approach of locking the gain spectrum in semiconductor lasers toward the integration on an uncooled chip. The changes in the band gap and the refractive index of uniaxially [100] strained GaAs were studied. Using the microbeams of GaAs/Ge/Si, we have demonstrated the emission wavelength tuning for the GaAs layers, where the red shift of PL spectrum was induced by mechanical stressing of the microbeams, and the restoration of PL spectra by removing stressing. The results should be a proof-of-concept indicating that such strain engineering is capable of locking the gain spectrum.

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