Germanium-tin alloys: applications for optoelectronics in mid-infrared spectra

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We summarize our work of the optoelectronic devices based on Germanium-tin (GeSn) alloys assisted with the Si₃N₄ liner stressor in mid-infrared (MIR) domains. The device characteristics are thoroughly analyzed by the strain distribution, band structure, and absorption characteristics. Numerical and analytical methods show that with optimal structural parameters, the device performance can be further improved and the wavelength application range can be extended to 2~5 μm in the mid-infrared spectra. It is demonstrated that this proposed strategy provides an effective technique for the strained-GeSn devices in future optical designs, which will be competitive for the optoelectronics applications in mid-infrared wavelength.

Keywords: optoelectronics; germanium-tin alloys; mid-infrared spectra

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Introduction

It is known to all that Group IV semiconductors have been widely applied in electronic devices due to their compatibility with mature complementary metal-oxide-semiconductor (CMOS) technologies and excellent electronic transport properties. However, low luminous efficiency caused by their indirect-bandgap limits their applications in photonic functional devices. Recently, a new technology based on incorporating Sn into Ge has triggered a tremendous interest for the accessibility of the direct bandgap material. The pioneering work has been made by R. Soref and C. H. Perry in ref. 7. After that, subsequent theoretical studies revealed that an indirect-bandgap material can be tuned to be a direct-bandgap one by increasing the substitutional Sn concentration in the Ge lattice. Moreover, the incorporation of Sn in the Ge lattice not only yields significant red shifts in the bandgap energies but also makes it a possible candidate as the gain medium, which indicates the potential applications of photonics in the mid-infrared (MIR) regions. Up to now, different kinds of efficient devices based on GeSn have been fabricated, including photodetectors and lasers with a response up to 2 μm.

However, there is a trade-off between high Sn composition and direct bandgap in GeSn based devices due to the fact that solid solubility resulting from high Sn composition would be destructive to the overall function of the optoelectronic device. Furthermore, the thermal stability of GeSn film caused by high Sn content becomes an obstacle to device fabrication. By inducing a tensile strain into GeSn alloys, the Sn composition can be reduced to achieve direct bandgap compared with the relaxed one, benefiting their light emission efficiency. Therefore, silicon nitride (Si₃N₄) films are used as an external stressor to induce tensile or compressive strain into semiconductor, which poses a strategy to improve the optical performance of the strained GeSn-based structures.

We sum up the work of different kinds of optoelectronic devices based on GeSn alloys with the assistance of the Si₃N₄ liner stressor. Analytical calculations show that the tensile strain induced by Si₃N₄ liner in GeSn contributes to both device performance and the extension of
optical absorption spectrum. It is demonstrated that the proposed strategy could expand the application spectrum of group IV based devices, which will find important applications in the novel optoelectronic applications.

**Device design and characteristic**

**Photodetector**

It is worth noting that employing the tensile strained GeSn alloys achieves a material with improved absorption coefficient \(a\) in MIR ranging, which provides an effective technique for extending the absorption edge of GeSn to mid-infrared wavelength. Here, we discuss three photodetectors based on different strained GeSn architectures. Figure 1(a) shows a conceptual illustration of the GeSn on Si on oxide undercladding pedestal (SOUP) waveguide. The 3-D schematics of GeSn pillar and fin array detectors are shown in Fig. 1(b) and 1(c), respectively. The tensile strain is introduced in the GeSn material by the Si\(_3\)N\(_4\) liner stressor.

![3D schematics of the designed GeSn photodetectors based on different architectures](image)

To better analyze the influence of the strain on the energy band, the \(E-k\) energy band diagrams of the relaxed and tensile strained Ge\(_{0.90}\)Sn\(_{0.10}\) in three different detectors are plotted and compared in Fig. 2. It is observed that in contrast to relaxed GeSn, the \(E_{G,F}\) is obviously reduced in tensile strained GeSn because there is a decline in the energy of \(\Gamma\) conduction valleys. It is clear that the \(E_{G,F}\) of tensile strained GeSn in pillar detector exhibits a larger attenuation than that of fin detector. The impacts of geometric parameters on the energy band structure in fin and pillar detectors are discussed in detail in ref. 33.

![\(E-k\) energy band diagrams of relaxed and strained GeSn devices](image)

What’s more, the impact of Sn content on the \(E-k\) energy band for relaxed and tensile strained GeSn is analyzed in ref. 26. It is concluded that by utilizing the Si\(_3\)N\(_4\) liner stressor, the \(E_{G,F}\) of GeSn alloy can be reduced, which is potential to extend the cutoff wavelength of various photonic devices into the MIR region.

In order to evaluate the performance of the proposed photodetectors, we calculate the absorption coefficient \(a\), a key parameter for determining the detection spectrum of the detector, by equation (1):

\[
a(\hbar \omega) = \frac{a_0}{(2\pi)^2} \frac{2\mu}{\hbar^2} (\hbar \omega - E_{G,F})^{\frac{1}{2}} ,
\]

where \(\hbar\) is the reduced Plank constant \(\hbar / 2\pi\), \(\omega\) is the angular frequency, and \(\mu\) is the reduced mass, which can be calculated by \(m_0' + m_n'/(m_0' + m_n')\). The electron and
hole effective masses ($m_x^*$ and $m_y^*$) are extracted from $E$-$k$ energy band diagrams based on

$$ m^* = \left( \frac{1}{\hbar^2} \frac{d^2 E}{dk^2} \right). $$

The $\alpha_b$ is given by

$$ \alpha_b = \frac{2\pi e^2 E_{G,F} (E_{G,F} + \Delta)}{3n_0\epsilon_0 c m_e \epsilon_r (E_{G,F} + \frac{2\Delta}{3})}. \quad (2) $$

In equation (2), $\epsilon_r$ is the refractive index, $\epsilon_0$ is the vacuum permittivity, $c$ is the velocity of light, $m_e$ is the electron mass, and $\Delta$ is the spin-orbit splitting.

Figure 3(a) shows that the calculated absorption coefficient $\alpha$ is modeled as a function of optical wavelength for relaxed and strained Ge$_{0.90}$Sn$_{0.10}$ in fin and pillar array detectors with different geometric parameters. It can be clearly seen that the optical response spectra of both strained Ge$_{0.90}$Sn$_{0.10}$ fin and pillar detectors are wider than that of relaxed detector. Besides, the pillar detector exhibits a larger cutoff frequency than fin detector when $L_{pillar}$ and $T_{fin}$ are equal. With the decrease in fin and pillar dimensions, the cut-off wavelengths display an obvious redshift. It should also be noted that the cut-off wavelengths are extended to be 4.35 μm with the $L_{pillar}$ of 100 nm. As shown in Fig. 3(b), we investigate the impact of the Sn content on the cut-off wavelengths of both the relaxed and strained devices. A significant redshift of absorption edge can be obtained in the strained devices. Furthermore, the cut-off wavelength performs a greater improvement with a larger Sn composition. All the enhancements in the cut-off wavelength can be speculated that there is an attenuation in the $E_{G,F}$ of GeSn.

Optical modulators

In this section, we theoretically investigate tensile strained GeSn electro-absorption modulator based on the Franz-Keldysh (FK) effect. As depicted in Fig. 4, $\alpha$ is modeled as a function of wavelength for tensile strained GeSn waveguide modulators with different Sn content, which is calculated by ref. 8. During simulation, the intensity of electric field varies from 0 to 10 MV/m at a step of 2 MV/m. Although Sn composition is different, the cut-off wavelength of all materials redshifts to MIR spectra range with the increase in the magnitude of electric

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**Fig. 3** (a) Comparisons of the absorption spectra of relaxed and strained GeSn in fin and pillar array detectors at the Sn content of 0.1. $L_{pillar}$ and $T_{fin}$ feature size varies from 100 nm to 500 nm in a step of 100 nm. (b) Calculated absorption spectra for relaxed and tensile strained GeSn waveguide photodetectors at different Sn content. Figure reproduced from: (a) ref. 8, IEEE; (b) ref. 26, Optical Society of America.

**Fig. 4** Modeled $\alpha$ as a function of wavelength at different electric fields at (a) Ge$_{0.97}$Sn$_{0.03}$, (b) Ge$_{0.95}$Sn$_{0.05}$, and (c) Ge$_{0.93}$Sn$_{0.10}$, respectively. Figure reproduced from ref. 26, Optical Society of America.
filed. Furthermore, it is found that the cut-off wavelength increases along with Sn content. To explore the optical transmission properties, here we employ the 2D finite-different time-domain (FDTD) method to model the Ge_{0.90}Sn_{0.10} waveguide modulator. Mode profiles of transverse electric (TE) and transverse magnetic (TM) modes in the tensile strained Ge_{0.90}Sn_{0.10} waveguide modulator are plotted at different wavelengths in Fig. 5. The refractive indexes for Ge_{0.90}Sn_{0.10}, Si_{3}N_{4}, and SiO_{2} are all extracted from ref. 35. Remarkably, single mode transmission can be observed in the waveguide for all the cases. Importantly, there is a leakage of light from waveguide with the increase in wavelength. In order to gain a deeper understanding on the optical transmission characteristics, the propagation loss versus wavelength is calculated for the tensile strained Ge_{0.90}Sn_{0.10} waveguide under different electric fields in Fig. 6. For both TE and TM modes, it shows a strong dependence of propagation loss on wavelength. The propagation loss increases along with the wavelength since the optical field becomes weakly confined in the waveguide, which corresponds to the mode profiles in Fig. 5. Moreover, for a fixed wavelength, the propagation loss increases with the increase of applied electric field due to the FK effect, which results in an enhancement in the modulation depth of GeSn waveguide electro-absorption modulator.

Lasers

Accessibility of the direct bandgap material makes GeSn a decent alternative to Si in the functional photonic platform, which helps to realize a monolithically integrated laser. A GeSn/SiGeSn multiple quantum well (MQW) laser wrapped in Si_{3}N_{4} liner stressor is proposed and investigated, as described in Fig. 7. The laser performances are thoroughly analyzed by Sn composition, injected carrier density \( n_{\text{injected}} \) and quantum well number \( n_{\text{well}} \).
demonstrated that the threshold current density $J_{th}$ reduces from 476 to 168 A/cm$^2$ and the optical gain is improved obviously, by introducing the Si$_3$N$_4$ liner stressor.

To analyze the impact of the Si$_3$N$_4$ liner stressor on the GeSn/SiGeSn MQW laser, strain distributions on the normal and radial cross section planes are plotted in Fig. 8. The strain along [100], [010], and [001] directions in the normal cross section plane are denoted by $\varepsilon_{[100]}$, $\varepsilon_{[010]}$, and $\varepsilon_{[001]}$, respectively. The strain contour plots indicate that [100] and [010] directions are under a tensile strain while $\varepsilon_{[001]}$ is compressive. At the center of the GeSn layer of GeSn/SiGeSn MQW laser, it can be seen that the values of $\varepsilon_{[100]}$, $\varepsilon_{[010]}$, and $\varepsilon_{[001]}$ are 0.85%, 0.85%, and -0.77%, respectively.

As shown in Fig. 9(a) and 9(b), the threshold current density $J_{th}$ and optical gain $\alpha$ in GeSn/SiGeSn lasers are modeled as a function of Sn composition in GeSn wells and injected current density, respectively. Here, $L_z$ is the thickness of the potential well. By introducing the tensile strain, there is an obvious attenuation in the $J_{th}$ in Ge$_{0.90}$Sn$_{0.10}$/Si$_{0.161}$Ge$_{0.695}$Sn$_{0.144}$ MQW laser. It can be clearly seen that the $J_{th}$ decreases from 476 to 168 A/cm$^2$ at a Sn content of 0.1. For comparison, the values of $\Gamma_{MQW, TE\cdot g\Gamma}$ and $\Gamma_{MQW, TM\cdot g\Gamma}$ are calculated as a function of injected current density $J$ for the relaxed and tensile strained Ge$_{0.90}$Sn$_{0.10}$/Si$_{0.161}$Ge$_{0.695}$Sn$_{0.144}$ MQW lasers, as shown in Fig. 9(b). The calculation results indicate that $J$ decreases significantly to achieve a same $\alpha$ for the strained Ge$_{0.90}$Sn$_{0.10}$ device.

It should also be noted that compared to the Ge$_{0.90}$Sn$_{0.10}$/Si$_{0.161}$Ge$_{0.695}$Sn$_{0.144}$ laser, Ge$_{0.96}$Sn$_{0.04}$/Si$_{0.274}$Ge$_{0.611}$Sn$_{0.115}$ device performs an improved $J$ under the same tensile strain, indicating the influence of the Sn component.

To better understand the impact of the gain medium on photoluminescence inside the cavity, a brief introduction is presented from the energy band structure. The subband energy difference between $E_{\Gamma}$ and $E_L$ is defined as $\Delta E$. Here, $E_{\Gamma}$ and $E_L$ are the energies of the ground sub-band levels of $\Gamma$ and $L$ valleys, respectively. Large density of the states concentrates in L-bandedge due to the fact that the effective mass is large. It is recognized that injected carriers occupy firstly lower energy states. Consequently, there is a larger carrier leakage for large $\Delta E$ and a small value of $\Delta E$ of the material is preferable to increase the gain. Energy band structure and carrier distribution in GeSn/SiGeSn MQW are discussed in detail in ref. 36. According to the discussion above, under tensile strain, the band structure is changed. During the injec-

Fig. 8 | Contour plots for (a) $\varepsilon_{[100]}$, (b) $\varepsilon_{[010]}$, and (c) $\varepsilon_{[001]}$ in the normal cross section plane and (d) $\varepsilon_{[100]}$, (e) $\varepsilon_{[010]}$, and (f) $\varepsilon_{[001]}$ in the radial cross section plane in GeSn well for the Ge$_{0.90}$Sn$_{0.10}$/Si$_{0.161}$Ge$_{0.695}$Sn$_{0.144}$ MQW laser wrapped in a 500 nm Si$_3$N$_4$ liner stressor. Figure reproduced from ref. 36, IEEE.
tion of carriers, the population inversion between the sub-bandgap $E_{\text{sub-G}}$ in GeSn wells occurs for the increase of electron occupation probability in $\Gamma$ conduction valley, which contributes to the improvement of light emission performance in lasers. It is believed that the Sn compositions at well layers and the strain should be carefully designed to achieve a large optical gain.

Light-emitting diode

In consideration of few experimental studies on the tensile strained GeSn light emitters up to date, we theoretically design and analyze a GeSn/SiGeSn double heterostructure (DH) light emitting diode (LED) with a microdisk structure wrapped in Si$_3$N$_4$. The impacts of Sn content on strain distributions and energy band structure are thoroughly analyzed. Moreover, the analysis of simulation results shows that the spontaneous emission rate $r_{sp}$ and the internal quantum efficiency $\eta_{IQE}$ can be improved by increasing Sn composition, carrier injection density $n_{\text{injected}}$ and n-type doping concentration $n_{\text{doping}}$ in the GeSn active layer. The 3D schematic of a GeSn/SiGeSn DH LED with a microdisk device architecture is shown in Fig. 10.

Since the light-emitting performance of the devices is dependent on $r_{sp}$ and $\eta_{IQE}$, we first focus on $r_{sp}$. Detailed calculation of $r_{sp}$ per unit volume in the energy and $\eta_{IQE}$ can be seen in the ref. The values of $\varepsilon_{[001]}$, $\varepsilon_{[010]}$, and $\varepsilon_{[001]}$, and volume strains in the central region for intrinsic GeSn layers are determined by the finite element method (FEM), which are extracted and compared in Fig. 11(a). One can see that there is no more change in the strain distribution. Figure 11(b) gives the $E_G$, $E_L$, and $E_{\Gamma L}$ of the relaxed and strained GeSn with different Sn compositions. It can be observed that under the tensile strain, the energy of the $\Gamma$ conduction valley and L conduction valley declines with the increase in Sn content. It should also be noted that the energy of the $\Gamma$ conduction valley decreases more significantly than that of the L conduction valley, which leads to a decline of Sn content required for achieving the direct bandgap.

Since the light-emitting performance of the devices is dependent on $r_{sp}$ and $\eta_{IQE}$, we first focus on $r_{sp}$. Detailed calculation of $r_{sp}$ and $\eta_{IQE}$ can be seen in the ref. As depicted in Fig. 12, the total spontaneous emission spectra of the proposed device are plotted under different conditions. Considering that there are two valence bands (e.g. a light hole (LH) band and a...
heavy hole (HH) band), \( r_{sp,\text{LH}} \) and \( r_{sp,\text{HH}} \) are calculated, respectively, corresponding to two peaks in the spontaneous emission spectrum. Compared to the relaxed one, \( r_{sp} \) can be improved markedly in the strained device. Figure 12(b) compares the total spontaneous emission spectra with different Sn compositions. It can be clearly seen that with the same \( n_{\text{injected}} \), the spontaneous emission spectra of the strained GeSn increase with the Sn content. With the same doping condition, a rapid increase in the intensity can be observed in Fig. 12(c), suggesting the similar impact of Sn content and \( n_{\text{injected}} \) on the strength of spontaneous emission rate. Besides, it is worth noting that the increases of Sn composition and \( n_{\text{injected}} \) bring about an opposite shift of peak position. That is, the red-
shift is caused by increasing Sn composition while the blueshift results from improved $n_{\text{injected}}$. Figure 12(d) describes the impact of $n_{\text{doping}}$ on $\tau_{\text{SRH}}$, which shows that $\tau_{\text{SRH}}$ can exhibit an enhancement with the increase in the n-type doping concentration $n_{\text{doping}}$.

As another key factor to evaluate the light-emitting performance of the devices, the IQE is calculated as a function of Sn composition in Fig. 13. The defect-eliminated carrier lifetime is denoted by $\tau_{\text{SRH}}$, which can be increased by improving the material quality of GeSn. It seems that IQE can be improved along with Sn content in GeSn layer and the devices with a large $\tau_{\text{SRH}}$ achieve an enhancement in IQE compared to those with a small $\tau_{\text{SRH}}$. It can be seen from Fig. 13(a) that IQE of DH LEDs is enhanced significantly after introducing tensile strain for the increase of $n_{\text{total}}$ in the tensile strained GeSn. Here, the total electron concentration $n_{\text{total}}$ is the sum of those in $\Gamma$ and L valleys ($n_{\text{L}}+n_{\text{L}}$). The impacts of $n_{\text{injected}}$ and $n_{\text{doping}}$ on IQE are investigated and shown in Fig. 13(b) and 13(c). It seems that IQE shows similar $n_{\text{injected}}$-dependence and $n_{\text{doping}}$-dependence like $\tau_{\text{SRH}}$. That is, the increase of $n_{\text{injected}}$ and $n_{\text{doping}}$ can also improve IQE of the devices.

**Outlook and summary**

In the last part of this section, we will briefly discuss the possible future avenues in GeSn material. Considering that band gap can be adjusted by adding Sn content, GeSn material can be applied for light emitting devices, including laser and LED. It has been reported that the related work is underway in laser and light emission. However, most of work is just focused on optical pumping at low temperature and the luminous efficiency is low. GeSn material with direct bandgap leads to a small band gap (i.e., ~0.56 eV), which limits its applications in optical communication. Besides, the existence of solid solubility and limitation of strain engineering also influence the performance of GeSn based devices. Above all, the photodetector with GeSn is potential for the feasibility of practical applications. It is demonstrated that there are already some achievements in photodetection and imaging laser and LED. It has been reported that the related work is underway in laser and light emission. However, most of work is just focused on optical pumping at low temperature and the luminous efficiency is low. GeSn material with direct bandgap leads to a small band gap (i.e., ~0.56 eV), which limits its applications in optical communication. Besides, the existence of solid solubility and limitation of strain engineering also influence the performance of GeSn based devices. Above all, the photodetector with GeSn is potential for the feasibility of practical applications. It is demonstrated that there are already some achievements in photodetection and imaging laser and LED.

**Conclusion**

In summary, we discuss the recent achievements in the applications of GeSn based devices wrapped by the Si3N4 liner stressor. Their strain distribution is analyzed in detail by numerical simulation tools, which is introduced by the Si3N4 liner stressor. The calculations show that the performance can be improved by optimizing the geometric parameters. Importantly, the operating wavelength can be extended to the whole mid-infrared (2–5 μm) region, which paves the way for the monolithic and CMOS-compatible mid-infrared integrated optics applications like image sensors and optical receivers.

**References**

1. Mathews J, Beeler R T, Tolle J, Xu C, Roucka R et al. Direct-gap photoluminescence with tunable emission wavelength in Ge$_{1-y}$Sn$_y$ alloys on silicon. *Appl Phys Lett* 97, 221912 (2010).
2. Chen R, Lin H, Luo Y J, Hitzman C, Kamins T I et al. Increased photoluminescence of strain-reduced, high-Sn composition Ge$_{1-y}$Sn$_y$ alloys grown by molecular beam epitaxy. *Appl Phys Lett* 99, 181125 (2011).
3. Liu H, Chen R, Lu W S, Luo Y J, Kamins T I et al. Investigation of the direct band gaps in Ge$_{1-y}$Sn$_y$ alloys with strain control by photoreflectance spectroscopy. *Appl Phys Lett* 100, 102109 (2012).
4. Yin W J, Gong X G, Wei S H. Origin of the unusually large...
band-gap bowing and the breakdown of the band-edge distribution rule in the Sn$_{1-x}$Ge$_x$$_2$ alloys. Phys Rev B 78, 161203 (2008).

5. de Guevara H P L, Rodriguez A G, Navarro-Contreras H, Vidal M A. Structural and optical properties of Ge$_{1-x}$Sn$_x$ alloys grown on GaAs (001) by R. F. Magneton Sputtering. ECS Trans 64, 393–400 (2004).

6. D’Costa V R, Cook C S, Birdwell A G, Litter C L, Canonicco M et al. Optical critical points of thin-film Ge$_{1-x}$Sn$_x$ alloys: A comparative Ge$_1$-Sn$_1$-Si$_1$ study. Phys Rev B 73, 125207 (2006).

7. Soref R A, Perry C H. Predicted band gap of the new semiconductor SiGeSn. J Appl Phys 69, 539–541 (1991).

8. He G, Atwater H A. Interband transitions in Sn$_x$Ge$_{1-x}$$_2$ alloys. Phys Rev Lett 79, 1937–1940 (1997).

9. Moontragoon P, Ikonic Z, Harrison P. Band structure calculations of Si-Ge-Sn alloys: achieving direct band gap materials. Semicond Sci Technol 22, 742–748 (2007).

10. Eckhardt C, Hummer K, Kresse G. Indirect-to-direct gap transition in strained and unstrained Sn$_{1-x}$Ge$_x$$_2$ alloys. Phys Rev B 89, 165201 (2014).

11. Attiaoui A, Moutanabbir O. Indirect-to-direct band gap transition in relaxed and strained Ge$_{1-x}$Si$_x$Si$_2$ ternary alloys. J Appl Phys 116, 063712 (2014).

12. Wirths S, Ikonic Z, Tiedemann A T, Holländer B, Stoica T et al. Tensely strained GeSn alloys as optical gain media. Appl Phys Lett 98, 192110 (2011).

13. Wirths S, Geiger R, von den Driesh N, Muslger G, Stoica T et al. Lasing in direct-bandgap GeSn alloy grown on Si. Nat Photonics 9, 88–92 (2015).

14. Soref R, Kouvetsakis J, Tolle J, Menendez J, D’Costa V. Advances in SiGeSn technology. J Mater Res 22, 3281–3291 (2007).

15. Bauer M R, Taraci J, Tolle J, Zschmesaya A V G, Zollner S et al. Ge–Sn semiconductors for band-gap and lattice engineering. Appl Phys Lett 88, 2992–2994 (2006).

16. Kouvetsakis J, Zschmesaya A V G. New classes of Si-based photonic materials and device architectures via designer molecular routes. J Mater Chem 17, 1649–1655 (2007).

17. Sun G, Soref R A, Cheng H H. Design of a Si-based lattice-matched ternary room-temperature Ge$_x$Ge$_{1-x}$Sn$_y$ multi-quantum-well mid-infrared laser diode. Opt Express 18, 19957–19965 (2010).

18. Gasseng A, Gencarelli F, Van Campenhout J, Shimura Y, Loo R et al. Ge$_x$SnGe heterostructure short-wave infrared photodetectors on silicon. Opt Express 20, 27297–27303 (2012).

19. Oehme M, Schmid M, Kaschel M, Gollhofer M, Widmann D et al. GeSn p–i–n detectors integrated on Si with up to 4% Sn. Appl Phys Lett 101, 141110 (2012).

20. Oehme M, Kostekci K, Schmid M, Oliveira F, Kasper E et al. Epitaxial growth of strained and unstrained Ge$_{1-x}$Sn$_x$ alloys up to 25% Sn. Thin Solid Films 557, 169–172 (2014).

21. Taoka N, Capellini G, von den Driesch N, Buca D, Zausmeil P et al. Sn migration control at high temperature due to high deposition speed for forming high-quality GeSn layer. Appl Phys Express 9, 031201 (2016).

22. Li H, Chang C, Chen T P, Cheng H H, Shi Z W et al. Characteristics of Sn segregation in Ge/GeSn heterostructures. Appl Phys Lett 105, 151906 (2014).

23. Wang W, Li L Z, Zhou Q, Pan J S, Zhang Z et al. Tin surface segregation, desorption, and island formation during post-growth annealing of strained epitaxial Ge$_{1-x}$Sn$_x$ layer on Ge (001) substrate. Surf Sci Data 321, 240–244 (2014).

24. Wang W, Dong Y, Zhou Q, Tok E S, Yeo Y C. Germanium-tin interdiffusion in strained Ge/GeSn multiple-quantum-well structure. J Phys D Appl Phys 49, 225102 (2016).

25. Gupta S, Magari-Köpe B, Nishi Y, Saraswat K C. Achieving direct band gap in germanium through integration of Sn alloying and external strain. J Appl Phys 113, 073707 (2013).

26. Zhang Q F, Liu Y, Yan J, Zhang C F, Hao Y et al. Theoretical investigation of tensile strained GeSn waveguide with Si$_x$N$_y$ linear stressor for mid-infrared detector and modulator applications. Opt Express 23, 7924–7932 (2015).

27. Fujisawa T, Tachih K. Material gain analysis of GeSn/SiGeSn quantum wells for mid-infrared Si-based light sources based on many-body theory. IEEE J Quantum Electron 51, 7100108 (2015).

28. Zhu Y H, Xu Q, Fan W J, Wang J W. Theoretical gain of strained Ge$_{1-x}$Si$_x$Sn$_y$ quantum well laser. J Appl Phys 107, 073108 (2010).

29. Zhang Q F, Liu Y, Yan J, Zhang C F, Hao Y et al. Simulation investigation of tensile strained GeSn fin photodetector with Si$_x$N$_y$ linear stressor for extension of absorption wavelength. Opt Express 23, 739–746 (2015).

30. Capellini G, Reich C, Guha S, Yamamoto Y, Lisser M et al. Tensile Ge microstructures for lasing fabricated by means of a silicon complementary metal-oxide-semiconductor process. Opt Express 22, 399–410 (2014).

31. Fanich C S, Chen X C, Chen R, Huang Y C, Chung H H. Strained pseudomorphic Ge$_{1-x}$-Sn$_x$ multiple quantum well microdisk using Si$_x$N$_y$ stressor layer. ACS Photonics 3, 2231–2236 (2016).

32. El Kurd M, Prost M, Ghibri A, Sauvage S, Checoury X et al. Direct band gap germanium microdisks obtained with silicon nitride stressor layers. ACS Photonics 3, 443–448 (2016).

33. Zhang Q F, Liu Y, Zhang C F, Huang Q Z, Hao Y et al. Tensile-strained mid-infrared GeSn detectors wrapped in Si$_x$N$_y$ linear stressor: theoretical investigation of impact of device architectures. IEEE Photonics J 7, 6803208 (2015).

34. Basu P K. Theory of Optical Processes in Semiconductors: Bulk and Microstructures (Oxford, UK: Clarendon, 1997).

35. Balik E D. Handbook of Optical Constants of Solids (San Diego: Academic, 1998).

36. Liu Y, Fang C Z, Gao X, Han G Q, Zhang Q F et al. Theoretical investigation of tensile-strained GeSn/SiGeSn multiple quantum well laser wrapped in Si$_x$N$_y$ stressor layer. IEEE Photonics J 10, 1500609 (2018).

37. Zhang Q F, Liu Y, Han G Q, Shao G, Yao X et al. Theoretical analysis of performance enhancement in GeSn/SiGeSn light-emitting diode enabled by Si$_x$N$_y$ stressor technique. Opt Appl 55, 9668–9674 (2016).

38. Al-Kabi S, Ghemini S A, Margetis J, Pham T, Zhou Y Y et al. Optically pumped Si-based edge-emitting GeSn laser. In Proceedings of Conference on Lasers and Electro-Optics 5W4C.1 (OSA; 2017); http://doi.org/10.1364/CLEO_SI.2017.W4C.1.

39. Stange D, von den Driesch N, Zabel T, Armand-Pifon F, Marzban B et al. Reduced threshold microdisk lasers from GeSn/SiGeSn heterostructures. In Proceedings of the 14th International Conference on Group IV Photonics 15–16 (IEEE, 2017); http://doi.org/10.1109/GROUP4.2017.8082173.

40. Margetis J, Al-Kabi S, Du W, Dou W, Zhou Y Y et al. Si-based GeSn lasers with wavelength coverage from 2–3 µm and operating temperatures up to 180 K. ACS Photonics 5, 827–833 (2018).

41. Millar R W, Dumas D C S, Gallacher K F, Jahanpar P, MacGreger C et al. Mid-infrared light emission from tensile strained GeSn microdisks. Opt Express 25, 39320–39329 (2017).
42. Stange D, von den Driesch N, Rainko D, Roesagaard S, Povstugar I et al. Short-wave infrared LEDs from GeSn/SiGeSn multiple quantum wells. Optica 4, 185–188 (2017).

43. Millar R W, Dumas D C S, Gallacher K, Jahandar P, Myronov M et al. Tensile strained GeSn mid-infrared light emitters. In Proccedings of the 14th International Conference on Group IV Photonics 49–50 (IEEE, 2017); http://doi.org/10.1109/GROUP4.2017.8082190.

44. Ghetmiri S A, Du W, Margetis J, Mosleh A, Cousar L et al. Direct-bandgap GeSn grown on silicon with 2230 nm photoluminescence. Appl Phys Lett 105, 151109 (2014).

45. Grant P C, Dou W, Alharthi B, Grant J M, Mosleh A et al. Comparison study of the low temperature growth of dilute GeSn and Ge. Jf Vac Sci Technol B Nanotechnol Microelectron Mater Process Meas Phenom 35, 061204 (2017).

46. Chen N L, Lin G Y, Zhang L, Li C, Chen S Y et al. Low-temperature formation of GeSn nanocrystallite thin films by sputtering Ge on self-assembled Sn nanodots on SiO2/Si substrate. Jpn J Appl Phys 56, 050301 (2017).

47. Grant P C, Dou W, Alharthi B, Grant J M, Mosleh A et al. Comparison study of the low temperature growth of dilute GeSn and Ge. Jf Vac Sci Techno B Nanotechnol Microelectron Mater Process Meas Phenom 35, 061204 (2017).

48. Chen N L, Lin G Y, Zhang L, Li C, Chen S Y et al. Low-temperature formation of GeSn nanocrystallite thin films by sputtering Ge on self-assembled Sn nanodots on SiO2/Si substrate. Jpn J Appl Phys 56, 050301 (2017).

49. Khiangte K R, Rathore J S, Schmidt J, Osten H J, Laha A et al. Wafer-scale all-epitaxial GeSn-on-insulator on Si(111) by molecular beam epitaxy. https://arxiv.org/pdf/1802.03150.

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Competing interests
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