IEIE Transactions on Smart Processing and Computing, vol. 4, no. 5, October 2015
http://dx.doi.org/10.5573/IEIESPC.2015.4.5.318

IEIE Transactions on Smart Processing and Computing

Strained Ge Light Emitter with Ge on Dual Insulators for Improved Thermal Conduction and Optical Insulation

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Received October 14, 2015; Revised October 21, 2015; Accepted October 25, 2015; Published October 31, 2015

** Regular Paper*

***Abstract*: We present a new way to create a thermally stable, highly strained germanium (Ge) optical resonator using a novel Ge-on-dual-insulators substrate. Instead of using a conventional way to undercut the oxide layer of a Ge-on-single-insulator substrate for inducing tensile strain in germanium, we use thin aluminum oxide as a sacrificial layer. By eliminating the air gap underneath the active germanium layer, we achieve an optically insulating, thermally conductive, and highly strained Ge resonator structure that is critical for a practical germanium laser. Using Raman spectroscopy and photoluminescence experiments, we prove that the novel geometry of our Ge resonator structure provides a significant improvement in thermal stability while maintaining good optical confinement.

***Keywords*: Strain, Germanium, Light emitter, Optical interconnects, Thermal conduction

1. Introduction

As electrical interconnects in computer chips are reaching their physical limitations in terms of power consumption and bandwidth, researchers have been intensively investigating possible candidates that can replace the electrical wires [1, 2]. Among various technologies, optical interconnects have become the strongest candidates due to their superior bandwidth and low power consumption if successfully integrated [3]. Although most of the critical components for optical interconnects, such as waveguides, modulators, and photo-detectors, have been successfully integrated on silicon (Si) substrates over the past few years, efficient and compact light sources on Si have yet to be demonstrated [4-9].

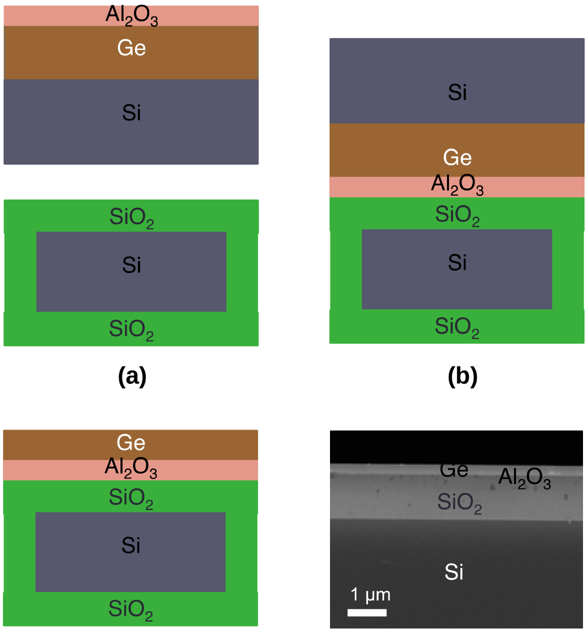
The main reason behind the absence of efficient light sources on Si can be attributed to the intrinsic material properties of group IV semiconductor components like Si and germanium (Ge). Because they both have an indirect bandgap property, most of the excited electrons reside in the lower indirect (L) conduction valley, rather than the direct (Γ) conduction valley [10]. Therefore, internal quantum efficiency (IQE) is extremely low for both Si and Ge [11, 12]. There are various methods that help overcome the indirect bandgap property, such as heavy n-type doping and mechanical tensile strain [13-18]. Previously, Dutt et al. performed in-depth theoretical calculations to investigate the effect of both n-type doping and tensile strain on the performance of Ge light sources, and they concluded that mechanical tensile strain is the most promising route towards a practical group IV light source [10]. Tensile strain in Ge can basically reduce the energy difference between the L and Γ valleys in Ge, resulting in increased IQE [19]. Interestingly, at ~1.7% biaxial and ~4.6% uniaxial tensile strain, the Γ conduction valley becomes lower than the L conduction valley, meaning that the indirect bandgap Ge can be transformed into a direct bandgap Ge [20, 21]. Due to this strikingly interesting feature of Ge, there has been intensive research into inducing large tensile strain in Ge.

Initial research effort was put into creating thin-film Ge membranes suspended in air, and then transferring external strain via various methods, such as water pressure, gas pressure, and stressor layer [17, 22-28]. More recently, a few researchers have presented novel structures to induce large tensile strain in Ge, in which a small residual tensile strain in Ge can be greatly amplified due to geometric effects [29-32]. In this structure, it is essential to release the whole structure by undercutting a sacrificial layer underneath the Ge layer. Uniaxial tensile strains of >4%

have been successfully demonstrated, and photoluminescence (PL) results have proven that the IQE of Ge can be significantly improved with strain [19, 32].

While a large mechanical strain can be effectively introduced in Ge wires and can also be conveniently tuned by the geometric effect, the whole structure remains suspended in air [30]. This structural feature of being suspended in air is advantageous in terms of optical confinement when optical cavities are integrated into these highly strained Ge bridges because of a large refractive index difference between air and Ge. However, it becomes extremely difficult to remove heat from the active Ge layer due to the absence of effective thermal conduction paths in the vertical direction. For a practical group IV laser with highly strained Ge as a gain medium, it is critical to achieve an improved thermal conduction path as well as excellent optical confinement through the large refractive index difference.

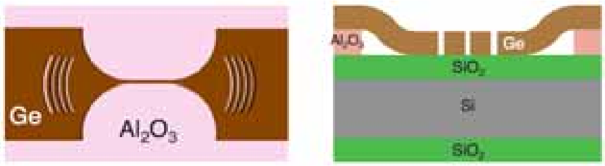
Therefore, in this paper, we introduce a novel substrate, Ge-on-dual-insulators (GODI), which allows us to induce a large tensile strain in Ge while obtaining both excellent optical confinement and improved thermal conduction. We fabricated a material stack composed of Ge, aluminum oxide (Al_2O_3), thermal oxide, and Si, instead of a conventional material stack with Ge, thermal oxide, and Si [12]. The addition of the thin (~25nm) Al_2O_3 enables us to release the Ge layer by undercutting only the thin Al_2O_3 layer. We will show that upon undercut, the Ge layer will bond to the oxide layer via van der Waals force, while Ge becomes highly strained because of geometric amplification of the strain. Through Raman spectroscopy and PL measurements, we compare two distinct devices, one suspended in air and another stuck on oxide, in terms of thermal conduction and optical emission properties.



(a) **(b)**

(c) **(d)**

Fig. 1. Fabrication process flow for creating Ge-on-dual-insulator substrates.



(a) **(b)**

Fig. 2. Schematics of a typical Ge light emitter with a Bragg reflector. (a) Top view. (b) Cross-sectional view.

2. Fabrication Process

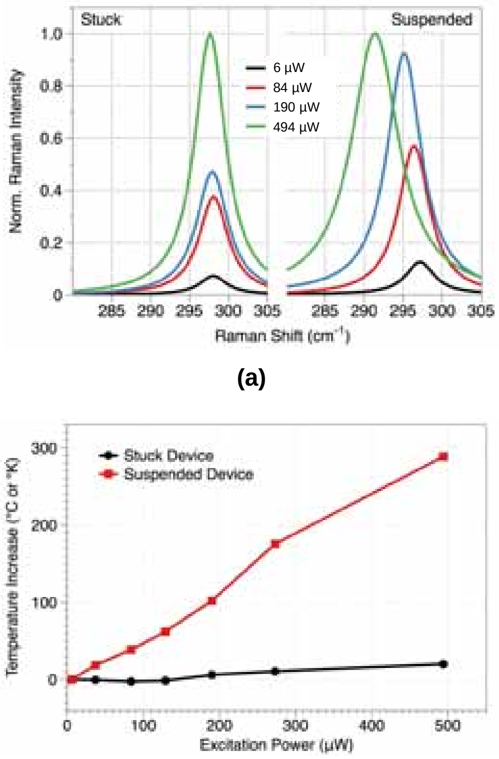
Fig. 1 shows a detailed fabrication process flow for creating our GODI substrate. We first grow a 2-μm thick Ge layer on Si using multiple hydrogen annealing heteroepitaxy (MHAH) to achieve a high-quality Ge layer at the top surface [33]. Although there exists a highly defective layer with numerous threading dislocations arising from lattice mismatch between Si and Ge, this MHAH growth technique effectively confines most threading dislocations close to the Si/Ge interface, thereby leading to a high-quality Ge layer towards the top surface. Note that the Ge layer is slightly tensile strained (~0.2%) due to thermal expansion mismatch between Si and Ge [14]. Because direct wafer bonding requires an atomically flat surface for the bonding layer, we perform a short chemical-mechanical polishing (CMP) on the Ge surface. After cleaning the Ge surface, a 25-nm thick Al_2O_3 was deposited using atomic layer deposition (ALD). Separately, an Si wafer is thermally oxidized to obtain an oxide layer about 850 nm thick. The bonding surfaces of the two wafers, Al_2O3 and thermal oxide, are chemically activated and undergo direct wafer bonding at an ambient temperature. Subsequently, the bonded wafer is annealed at a high temperature (500°C) to increase bonding strength. Using tetramethylammonium hydroxide (TMAH), the Si part of the carrier wafer is removed while the handle Si wafer is protected by the thermal oxide layer. Because TMAH does not etch Ge, the chemical wet etching automatically stops at the Si/Ge interface of the carrier wafer. Finally, to remove the defective layer, which was originally close to the Si/Ge interface, CMP is performed until the Ge thickness becomes ~220 nm. Fig. 1(d) shows a cross-sectional scanning electron micrograph.

In order to test the effectiveness of our new GODI substrate for strained Ge laser structures in terms of optical confinement and thermal conduction, we patterned the Ge layer into a typical Ge wire structure with large pad areas for strain amplification within the wire region. Bragg reflectors were also integrated to complete the resonator structure, as shown in Fig. 2(a) [34]. Because of the small features of Bragg reflectors, we use electron beam lithography, followed by anisotropic dry etching. Lastly, Al_2O_3 is undercut using KOH through patterned areas, but Ge and oxide do not get etched. Upon undercut, the force in the large pad regions gets concentrated into the narrow wire region, thereby significantly increasing the tensile strain in the wire. While drying the sample of water after transferring it from KOH to water, the whole Ge layer gets stuck to the underlying oxide layer because of capillary and van der Waals force, as shown in Fig. 2(b). The strain in the Ge layer remains almost the same, whereas the whole Ge structure is now in close contact with the oxide layer, as shown in Fig. 3(a). To make a proper comparison between our new geometry and a rather conventional suspended Ge structure, we also created a control sample with the Ge layer fully suspended in air, as shown in Fig. 3(b). The clear halo along the [110] direction shows the undercut region under which there is an air gap.

3. Results and Discussion

To investigate how effectively the new resonator geometry from GODI can remove the accumulated heat at the active layer, we performed Raman spectroscopy. The 514-nm excitation laser acts as a point heat source, and by monitoring the change of optical phonon frequency as a function of excitation power, we can infer temperature variation in our Ge resonator. We also performed the same experiments on the suspended Ge resonator to compare the new (stuck) and traditional (suspended) devices. Fig. 4(a) shows the Raman spectra for various laser excitation powers for the stuck device (left half) and the suspended device (right half). As the power increases, Raman spectra for the suspended device downshift significantly, while for the stuck sample, the downshift is almost negligible up to the excitation power of 130 µW. This downshift of Raman spectra can be purely attributed to the temperature rise in Ge. According to Lugstein et al. [35], the temperature-shift coefficient for the first-order Stokes Raman band for Ge is 0.02 cm^{-1}/°C. Using this coefficient, one can plot the temperature variation in Ge as a function of the excitation power, as shown in Fig. 4(b). It is clear that the GODI heat removal from the Ge layer is significantly improved in the stuck device.

Although it is proven that the new geometric feature of the stuck Ge resonator from GODI attains a greatly improved thermal property, it is also equally important to maintain good optical confinement within the Ge layer. Unlike the suspended resonator with an air gap underneath the active Ge layer, the stuck resonator has an oxide layer with a relatively high refractive index. Therefore, it is critical to carefully choose the thickness of the underlying oxide layer to prevent the confined optical field from tunneling through the oxide layer. Using finite-difference time-domain (FDTD) optical simulations, we found that an oxide layer thicker than 400 nm allows us to confine the optical field as effectively as an air gap.

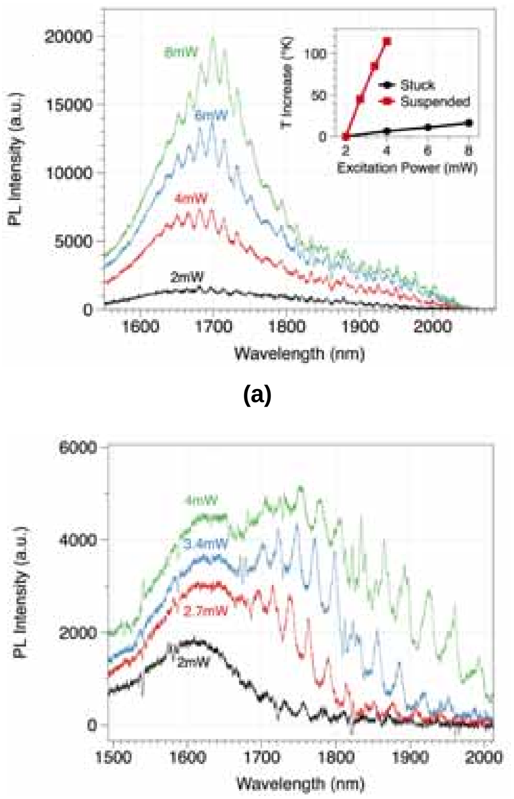


(b)

Fig. 4. (a) Raman shift spectra for the stuck (left half) and the suspended (right half) device for various excitation conditions, (b) Temperature increase as a function of laser excitation power.

To experimentally investigate the optical property of two resonators, we conducted room-temperature PL. A 980-nm excitation laser was focused on the center of our resonator structure and we collected the photon emission using a 50X objective lens. Figs. 5(a) and (b) show PL spectra from the stuck and suspended resonators, respectively, as a function of excitation laser power. The black curves for both figures are for the lowest excitation power level (2 mW). Note that the initial peak positions of the two spectra for the suspended and stuck resonators are slightly different because strain levels in the two structures are not the same due to the different amount of undercut. It should also be noted that even at the minimum power level for obtaining a reasonable PL spectrum (~2 mW), the temperature of Ge wires may have already been increased.

To investigate the effect of our new stuck device geometry on thermal conduction, we carefully examined how the resonance peaks shift as a function of excitation laser power. The shift of cavity resonances is due to the change of Ge's refractive index, which is directly associated to the temperature of Ge. As shown in Fig. 6, we first find from FDTD simulations that the resonance peak position at ~1700 nm shifts roughly by 4 nm for each 0.01 index increase. The refractive index change for each 20°C temperature increase is ~0.01, according to Li [36]. Therefore, one can infer that for each 4-nm resonance shift, Ge's temperature increases roughly by 20°C. In the stuck structure, resonance peak position shifts only ~1 nm as the excitation power increases from 2 mW to 4 mW, thereby implying a temperature increase of ~5°C. In the suspended structure, however, the resonance peak position shifts ~23 nm with the same power variation, meaning that Ge's temperature increases by >100°C. The inset of Fig. 5(a) shows the calculated temperature variation as a function of excitation power. Although the stuck device shows only a <20°C temperature rise with a 6-mW power increase, the temperature of the suspended device increases >100°C with only a 2-mW power increase. For both cases, the optical Q-factors are comparable, implying that the stuck devices can still attain strong optical confinement even



(a)

(b)

Fig. 5. (a) PL spectra for the stuck device at various excitation power levels. Inset: the temperature increase as a function of laser excitation power for both the stuck and suspended samples, (b) PL spectra for the suspended device at various excitation power levels.

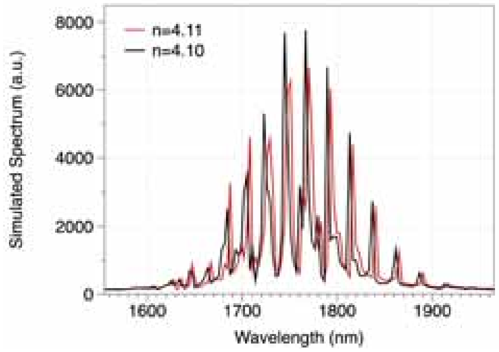


Fig. 6. (a) Simulated PL spectra for different refractive indices.

with the underlying oxide layer. Therefore, we conclude that the stuck device has superior thermal conduction, compared to the conventional suspended device, while maintaining good optical confinement.

4. Conclusion

To sum up, we present a new substrate named GODI that enables us to create strained Ge resonators with excellent optical confinement and improved thermal conduction. By using Al_2O_3 of dual dielectrics as a sacrificial layer, we eliminate the air gap in conventional strained Ge structures, which is the main cause of thermal conduction problems. Raman spectroscopy and PL measurements prove that the new device geometry from GODI can effectively remove the heat accumulated in the Ge layer due to the laser excitation. Also, through FDTD optical simulations and photoluminescence measurements, we show that having an oxide layer thicker than 400 nm can maintain a strong optical confinement within the Ge active layer. We believe that our new substrate can pave the way toward creating a thermally stable and highly strained Ge laser.

Acknowledgement

This work was also supported by an INHA university Research Grant.

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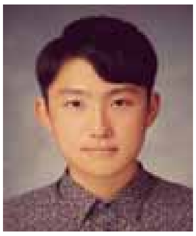

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