GeSnOI mid-infrared laser technology

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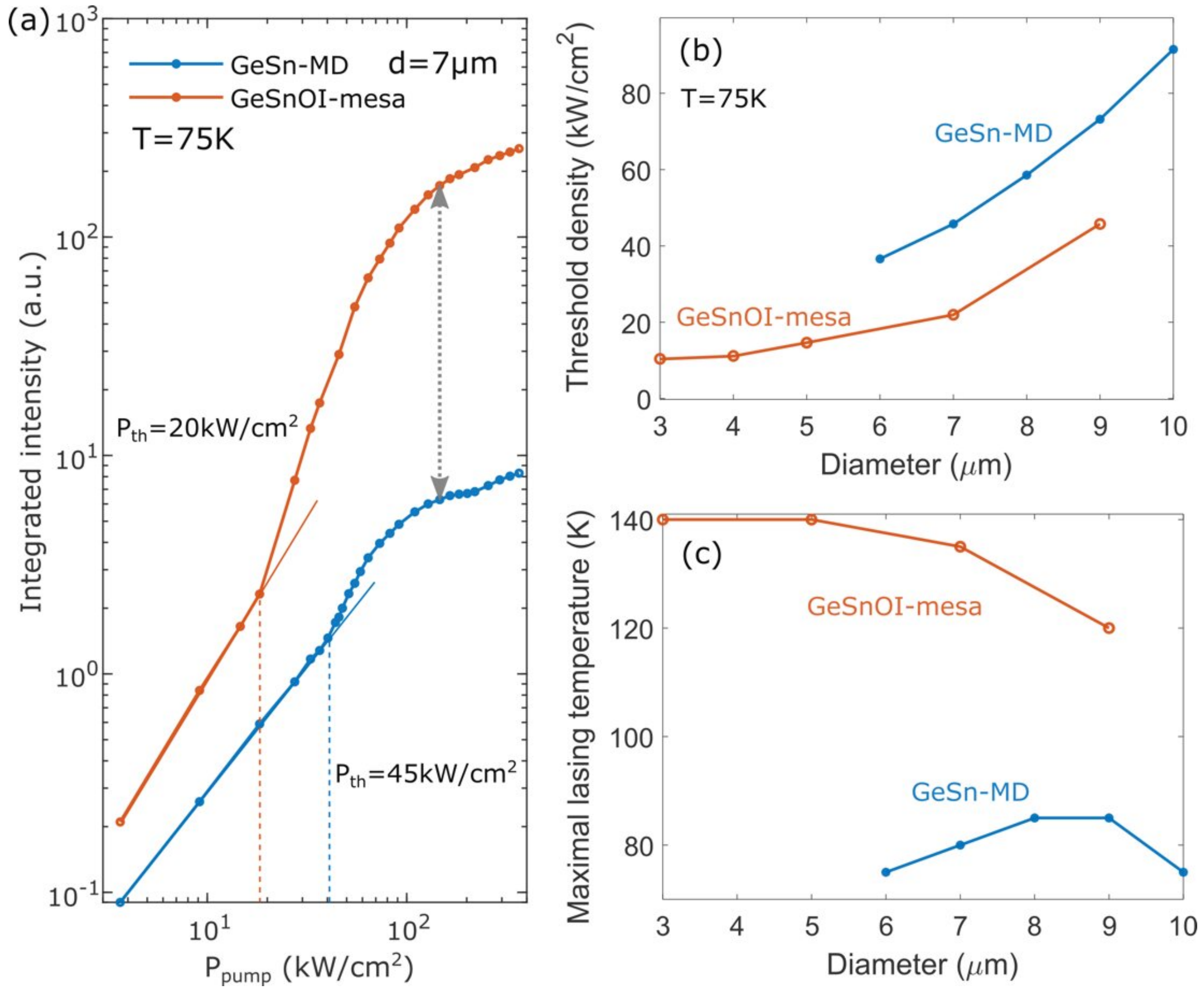


Laser performances with GeSnOI disk resonators as compared with those of conventional as-grown GeSn disks. (a) Light in-Light out curves. (b) Laser thresholds as a function of the disk diameter. (c) Maximum lasing temperature as a function of the disk diameter. Smaller disk diamter were not reachable with the as-grown GeSn layers because of their undercut. Credit: by Binbin Wang, Emilie Sakat, Etienne Herth, Maksym Gromovyi, Andjelika Bjelajac, Julien Chaste,

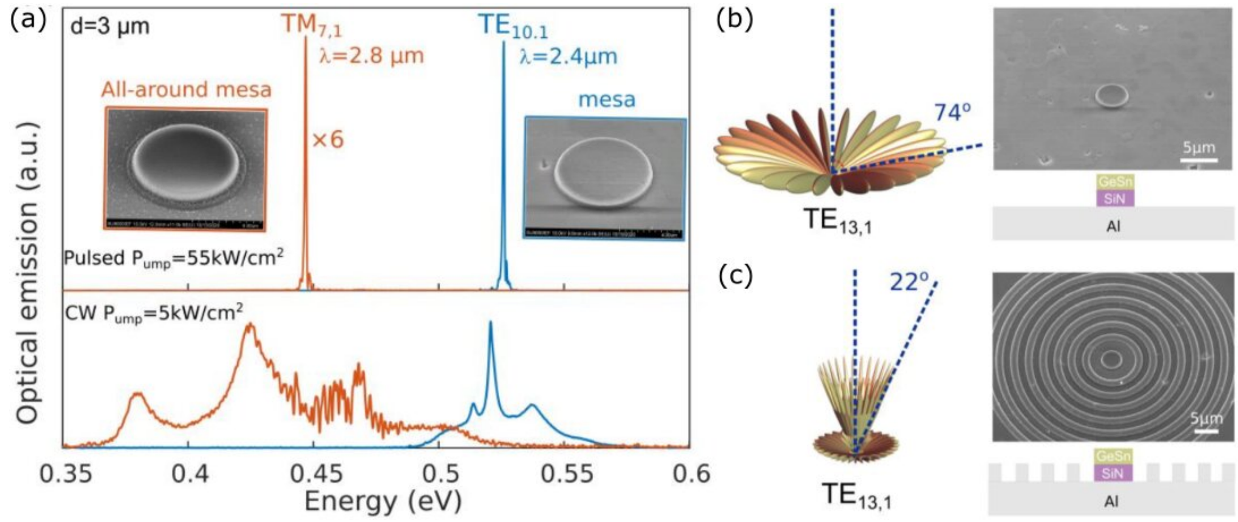
Gilles Patriarche, Philippe Boucaud, Frédéric Boeuf, Nicolas Pauc, Vincent Calvo, Jérémie Chrétien, Marvin Frauenrath, Alexei Chelnokov, Vincent Reboud, Jean-Michel Hartmann and Moustafa El Kurdi

Direct band gap GeSn alloys have emerged as a promising group-IV gain material for low-cost infrared laser manufacturing. They face major issues like high threshold power, and low lasing temperature that hinder their integration into full CMOS-compatible photonic chips. Scientists in France have developed a specific GeSn-on-insulator (GeSnOI) technology that combines defects, strain, electronic-band, modal, and thermal engineering all together. They show a GeSn laser on a versatile photonic platform with improved performances.

Low-cost and CMOS-compatible Si-based photonic technologies have enabled significant advances over the past few decades particularly for Datacom application and high speed optical links. However, a major bottleneck of monolithically integrated silicon photonic circuit is the lack of COMS-compatible lasers. This was principally due to the indirect nature of the electronic band structure of group IV semiconductors. Up to now, III-V lasers are the most standard and reliable light source on integrated platform. Nevertheless, the CMOS incompatible processes of III-V laser lead to high manufacturing cost and complex integration on silicon chip fabrication chain. Alternatively, group IV GeSn semiconductor alloys, that have a direct bandgap for tin contents larger than 7 %, are promising for CMOS-compatible and low-cost laser.

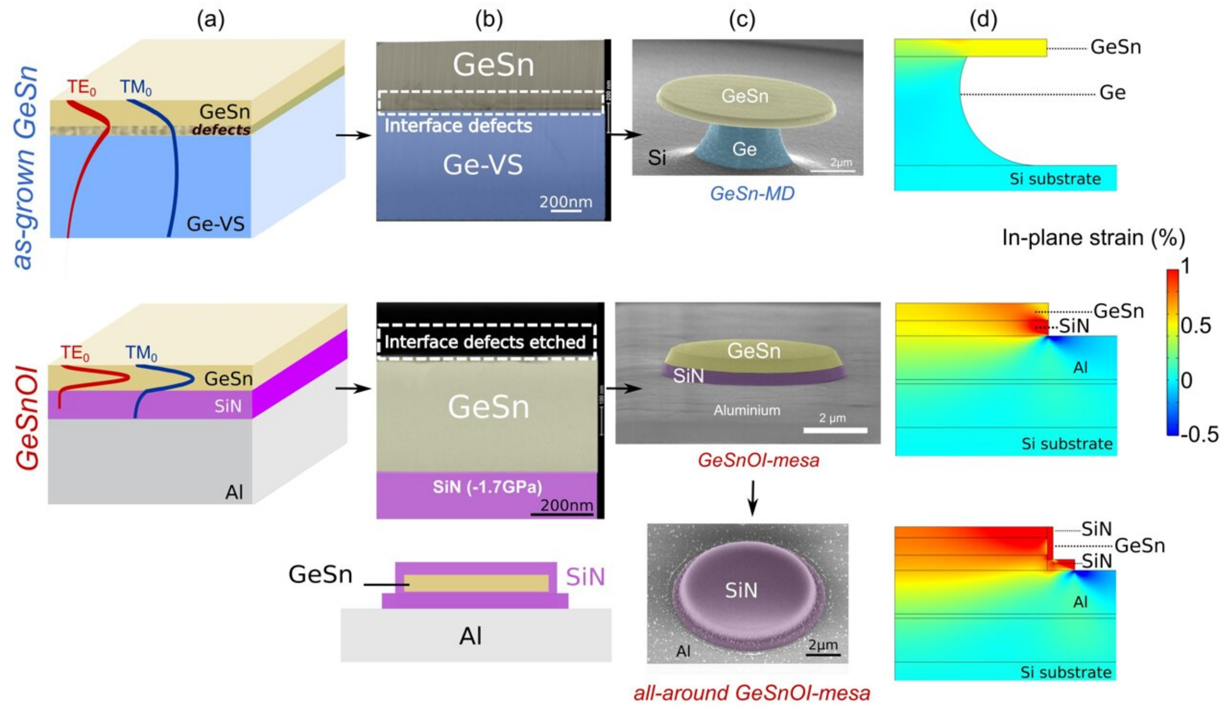
Since the first GeSn laser demonstrated in 2015, researches were focused on a GeSn laser designed on the basis of an as-grown GeSn layer on Ge strain-relaxed-buffer on silicon. The problem of it is that the lattice mismatch between GeSn and Ge induces a compressive strain. This is undesirable since compressive strain degrades the optical gain properties of the GeSn alloys by reducing their band structure directness. Compressive strain can even change the GeSn alloys band structure from direct to indirect, thus eliminating their gain properties.

Mainstream approaches were thus to growth thick GeSn layers above their critical thickness for plastic relaxation. This however yields the formation of very dense array misfit defects near the GeSn-Ge interface that introduce non radiative recombination process against lasing. Additionally, a residual compressive strain still remains in these cases. To compensate the effect of compressive strain, most of work of GeSn laser focus on the increase of Sn concentration. This method has enabled an improvement of the maximum lasing temperature of GeSn laser, but higher Sn content leads to more GeSn-Ge interface defect, and then higher excitation thresholds of the order of MW/cm^2. Additionally, the further increase of Sn concentration in GeSn is a big challenge since the equilibrium solubility of Sn in Ge is only 1%. Hence, GeSn lasers based on as-grown layer suffer from both the bottleneck on material growth and laser performances.



(a) Tunable lasing wavelength by top SiN strain layer. (b) and (c) show vertical redirection of whispering gallery mode laser with circular grating. Credit: by Binbin Wang, Emilie Sakat, Etienne Herth, Maksym Gromovyi, Andjelika Bjelajac, Julien Chaste, Gilles Patriarche, Philippe Boucaud, Frédéric Boeuf, Nicolas Pauc, Vincent Calvo, Jérémie Chrétien, Marvin Frauenrath, Alexei Chelnokov, Vincent Reboud, Jean-Michel Hartmann and Moustafa El Kurdi

In a new paper published in *Light Science & Application*, a team of scientists, led by Professor Moustafa El Kurdi from the Center for Nanosciences and Nanotechnologies, University of Paris-Saclay and co-workers from CEA in France, have developed a specific GeSn-on-insulator (GeSnOI) technology for high performance GeSn laser. They fabricated a GeSn-SiN-Al stack by using bonding processes on silicon wafer. The GeSnOI layer was then patterned into microdisk laser cavities. They demonstrated that this GeSnOI technology tackles lattice mismatch interface defects, compressive/tensile strain engineering, thermal management and optical confinement all together. Benefiting from this versatile technology, they developed a GeSn laser with a lower threshold, a higher maximum lasing temperature, and a stronger lasing intensity. The versatile GeSnOI platform additionally allows scientists to pave the way for multifunctional planar GeSn lasers, such as tunable laser wavelength by using SiN stressor layer as well as complex on chip light wave engineering. They indeed show vertical redirection of whispering gallery modes in-plane lasing from the GeSnOI disk resonator by addition of specifically designed circular grating.



(a) Schematic diagram with TE and TM polarized propagating waves intensity profile at 2.4 µm wavelength. (b) TEM images of as-grown GeSn layer and GeSnOI with removed interface defects. (c) SEM images of GeSn microdisk resonators based on as-grown layer and GeSnOI platform. (d) In-plane strain variation, analyzed by Finite Element modeling (FEM), of GeSn and GeSnOI microdisks that due to the different designs and processing adopted. Here we plot the strain relative to initial residual post-growth compressive strain of -0.5% for the GeSn layer. The SiN layer was computed with initial compressive stress that can relax thus inducing positive strain variation. The SiN stressor on top and bottom allows for homogenously distributed tensile strain injection in the GeSnOI disk without the need to undercut the active region. Credit: by Binbin Wang, Emilie Sakat, Etienne Herth, Maksym Gromovyi, Andjelika Bjelajac, Julien Chaste, Gilles Patriarche, Philippe Boucaud, Frédéric Boeuf, Nicolas Pauc, Vincent Calvo, Jérémie Chrétien, Marvin Frauenrath, Alexei Chelnokov, Vincent Reboud, Jean-Michel Hartmann and Moustafa El Kurdi

The GeSn-Ge interface defects of GeSnOI stack is fully removed by a simple top etching after transfer and bonding processes, resulting in better active layer quality and higher optical gain. The improved gain leads 60 times higher laser intensity, 55 K enhancement of the maximum lasing temperature and lower threshold in GeSnOI-based laser as compared to conventional as-grown GeSn approaches. The low index of the SiN layer provides strong optical confinement in GeSn layer without the need to undercut it. The SiN layer is also used as a stressor layer that enables additionally to transfer tensile strain to the GeSn active cavity, and then overcome the residual compressive strain issues.

This enables planar laser cavity designs with strain and modal management without the need to undercut the layer, for example a simple microdisk-mesa is herein used. By contrast, undercut is mandatory in traditional GeSn laser based on as-grown layers to deal with strain and modal engineering, furthermore the dense GeSn-Ge interface misfit defects remain in this case. The undercut yields with lower thermal disspation efficiency, especially for reduced disk diameter, here below 6 µm of diameter the structures were too fragile to provide lasing. Using a planar mesa based on GeSnOI platform combining with Al thermal sink, scientists observed laser in a meas disks as small as 3 µm in diameter, close to laser wavelength of 2.4 µm. This is the smallest GeSn laser disk shown up to now.

The versatile GeSnOI platform enables scientists to pave the way for multifunctional planar GeSn laser. For example, by deposition and partial etching of top SiN strain layer, they realize controllable tuning of lasing wavelength. With the help of Al circular grating, they redirect the laser emission direction from in-plane to out-plane.

"Other planar laser configurations, such as ridge Fabry-Perot waveguides, ring cavities or even complex photonic crystals, are possible by our GeSnOI platform. Another key advantage of this platform is its ability to combine passive mid-infrared SiN components and GeSn photodetectors and sources to develop a CMOS-compatible all group-IV integrated photonic circuit. It represents a new paradigm for infrared Group IV photonics in the 2-4 μm wavelength range and mitigate the need of III-V laser integration on silicon photonic chip." the scientists forecast. "This platform is completely compatible with electrically-driven GeSn devices and can even offer better performances. Our technology also heralds the appearance of the first room-temperature GeSn laser by simply increasing Sn content to available concentration." they added.

More information: Binbin Wang et al, GeSnOI mid-infrared laser technology, *Light: Science & Applications* (2021). DOI: 10.1038/s41377-021-00675-7

Provided by Chinese Academy of Sciences

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