Why Room Temperature GeSn Lasers Need Carbon

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***Abstract*—Device models show GeSn lasers are limited by weak electron and photon confinement. Adding carbon offers strong conduction band offsets, freeing SiGeSn layers for separate confinement heterostructures, reducing thresholds. Photoluminescence from recent growths of GeC and GeSnC quantum wells will be presented.**

***Keywords*—GeC, GeSn, silicon photonics, laser thresholds, laser modeling, optical mode, quantum well, highly mismatched alloys**

I. Introduction

Direct bandgap Group IV materials compatible with CMOS fabrication and CPU temperatures would enable lasers, amplifiers, and compact modulators intimately integrated for optical interconnects, as well as vector multiplication in a single clock cycle for dramatically faster image processing and machine learning. However, Group IV lasers operate with high thresholds even at cryogenic temperatures and/or optically pumped, curtailing their utility for integrated photonics.

In this work, we show that the high thresholds of Ge and GeSn lasers are due to three dimensions of weak confinement: electrons in *k*-space, electrons in real space, and photons. On the other hand, the addition of dilute amounts of carbon promises strong electron and photon confinement for a 2D density of states and separate confinement heterostructures, leading to low thresholds even at CPU temperatures. Unlike diamond or SiC alloys, the bandgap of $Ge_{1-x}C_x$ decreases with x.

II. Background and Methods

Population and laser gain and loss models used strained GeSn data from [1] and [2], and GeC(Sn) data from VASP [3]. Optical mode and confinement factor were calculated using a finite element solver. Finite quantum well (QW) energies and populations assumed isotropic, parabolic bands and Fermi-Dirac statistics. Only electrically pumped lasing is considered.

III. Confinement Calculation Results

A. *k-space: Heavy L Conduction Band Remains Populated*

Adding Sn to Ge can make it weakly direct: E_L-E_Γ < 80 meV in bulk material. However, because GeSn has a very small electron effective mass at Γ ($m_{e\Gamma}^* \lesssim 0.02\ m_0$), quantum confinement pushes the direct Γ valley back above or near the L valley. Even in "direct" material, the discrepancy between L and Γ masses means even in an ideal QW (Fig. 1, red arrow), almost half the electrons will still occupy the heavy, indirect L valley and higher Γ states instead. This greatly reduces differential gain and increases free carrier absorption (FCA).

Adding carbon as GeC or GeCSn provides strong directness due to a band anticrossing at Γ [4]. For 5-9 nm QWs, all electrons are in the Γ_1 state and can contribute to gain.

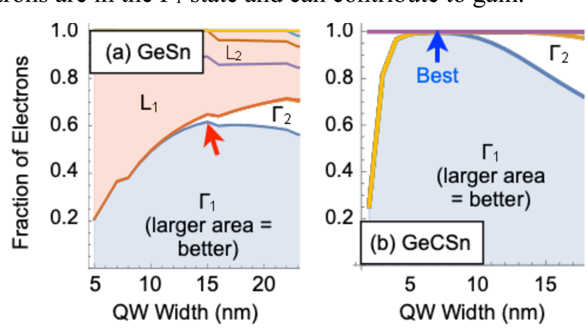

Fig. 1. Fraction of electrons in each confined state for (a) GeSn QW in SiGeSn barriers, and (b) GeC QW in Ge barriers, as a function of QW width. Blue regions represent fraction of electrons in Γ_1 state; pink is fraction in L states. Maximum differential gain $\partial g/\partial n$ when 100% of electrons are in Γ_1 state.

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B. *Real Space: Escape from Quantum Wells (QW)*

For maximum laser gain, QWs should be narrow enough that only a single state is confined, so all electrons contribute to gain. However, confinement in real space is reduced by narrowing the well; the raised QW ground state is closer to the height of the energy barriers, allowing escape out of the QW. This makes a 2D density of states (DOS) for low threshold GeSn/Ge lasers impractical, and direct gap quantum dots impossible.

In contrast, GeC(Sn) QWs not only start deeper, but $m^*_{e\Gamma} \approx$ 0.45-0.7 m_0 is >10x larger than GeSn and comparable with m^*_{eL}. Thus, the lowest direct CB state is preserved even in a 5 nm QW.

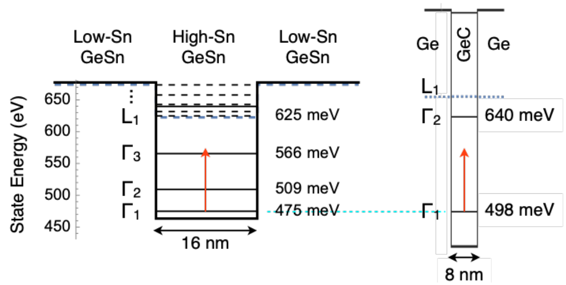

Fig. 2. Confined states in typical GeSn laser QW (left) and GeC QW (right). Red arrow shows $4k_BT$ at room temperature. Deeper GeC QW precludes both carrier escape to barrier and thermal population of higher QW states.

C. *Optical Confinement: Low Refractive Index Cladding*

GeSn QWs typically require relaxed, high-Sn buffer layers to reduce strain, but high Sn means high refractive index, pulling the optical mode away from the QWs [5,6], as shown in Fig. 3. Furthermore, because SiGeSn is needed for the barriers in GeSn QWs, its low index is unavailable for cladding layers.

Adding C to the QW frees SiGeSn for cladding layers and separate confinement heterostructures. This increases the optical confinement factor, which further reduces laser thresholds.

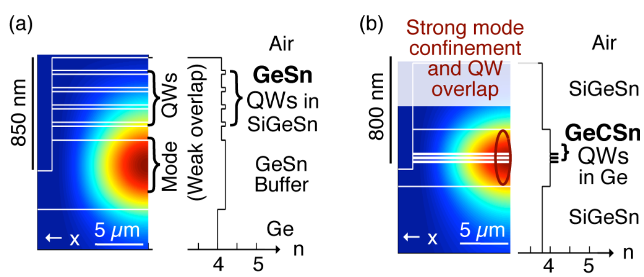

Fig. 3. Calculated optical mode and refractive index (n) profiles. (a) GeSn/SiGeSn (recalculated from Margetis). Large n in GeSn buffer pulls mode from QWs. (b) GeCSn/Ge 3QW with SiGeSn optical cladding layers for a confinement factor of up to 5% per QW.

IV. Gain, Loss, and Threshold

Using the standard laser relationships, $\Gamma_{opt}g_{th} = \langle\alpha_i\rangle + \alpha_m + \alpha_{FCA}$ and $J_{th} = qL_z(BN_{th}^2 + CN_{th}^2)/\eta_i$, we calculated threshold current density, J_{th}, for a double heterostructure (DH) GeSn laser with and without thermal dilution of electrons to higher QW states, and internal and FCA losses (α_i, α_{FCA}), using geometries similar to recent lasers [1]. The results suggest room temperature GeSn lasing might be possible, but at very high threshold current densities (Fig. 4). In contrast, adding C reduces thresholds below the lowest, ideal "Γ CB only" values shown in the figure.

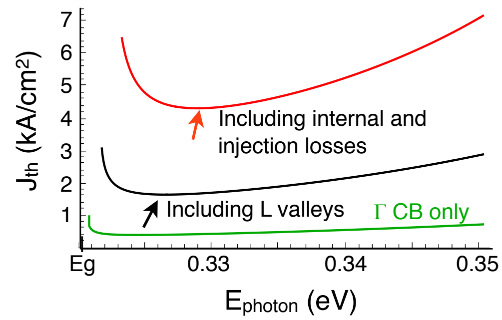

Fig. 4. Contributions to threshold current for DH GeSn laser. Populated L valleys add free carrier absorption, amplifying the effects of other losses. GeC(Sn) thresholds (not shown) remain entirely below the green bottom line.

We will discuss the influence of C on C and Sn incorporation into the GeCSn alloy films [7] and present photoluminescence (PL) and other characterization results from recent growth of GeCSn QWs showing high crystallinity and no Sn segregation. C and Sn each appear to improve the quality of growth of the other in Ge alloys.

V. Summary

The addition of dilute amounts of C directly addresses the greatest weaknesses in GeSn lasers: the lack of confinement in narrow QWs, the barely direct bandgap, a low optical confinement factor, and difficult growth. FCA losses compound the already-high thresholds. Room temperature electrically pumped lasers are unlikely with GeSn alone but appear to be achievable with the addition of dilute carbon.

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