Numerical investigation of optical gain in tensile strained germanium layers for near infra-red lasers

O Aldaghri, Z Ikonic and R W Kelsall

School of Electronic & Electrical Engineering,
University of Leeds,
Leeds LS2 9JT, UK.
r.w.kelsall@leeds.ac.uk

The field of silicon photonics has seen rapid development over the past few years, with high performance silicon-compatible modulators, detectors, filters and (de)multiplexers all demonstrated. The key missing component is a silicon-compatible light source. Whilst silicon is a very poor light emitter (except via the Raman process [1]), germanium holds much more promise, having a direct interband transition only ~140meV above the indirect band gap, and with an energy corresponding to a photon wavelength of 1.55um, an industry - standard communications wavelength. The direct optical transition in germanium can be enhanced by a combination of tensile strain (which reduces the Γ valley energy minimum relative to that of the L valley) and heavy n-type doping (which fills low-lying states in the L valley; hence increasing the probability that injected electrons will populate the Γ valley and thus contribute towards population inversion at or near the Γ point) – see fig. 1. Using this approach, both optically pumped and electrically injected laser operation have been reported [2,3]. The optically active Ge layer in the devices had a biaxial tensile strain level of ~0.2%, which results from the differing thermal contraction rates in epitaxial Ge and the underlying Si substrate, upon cooling from the Ge crystal growth temperature. However, other experimental studies have concluded that net gain is not possible in Ge structures with low levels of tensile strain, due to strong optical re-absorption[4].

In this work, we have calculated the material gain for tensile strained Ge for a range of strain values, doping densities, and carrier injection levels. We have also calculated the intervalence band absorption (IVBA) between heavy, light hole and spin-split-off bands, using an 8 band **k.p** bandstructure with strain corrections. Finally, to obtain the net gain, we have calculated the intra-conduction band optical absorption (ICBA), including both intra- and inter-valley transitions mediated by both phonons and ionised impurities, using second-order perturbation theory [5].

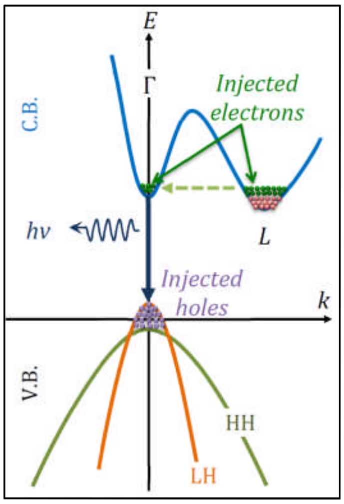

Fig. 1. Schematic diagram of the bandstructure of doped, tensile strained Ge, indicating how heavy n-type doping enhances electron injection into the Γ valley and hence increases the interband gain.

As expected, the material gain of Ge both increases and red-shifts with applied tensile strain (the latter due to the reduction in direct band gap) – see fig. 2. However, the IVBA also increases significantly with tensile strain, because the separation between the heavy and light hole bands increases, increasing the probability of absorption transitions. The IVBA also increases strongly with injected carrier density as shown in fig. 3.

When combining material gain, IVBA and ICBA, it is predicted that net gain can be achieved in n-type Ge, but only for biaxial tensile strain levels above ~0.9%, (fig. 4),

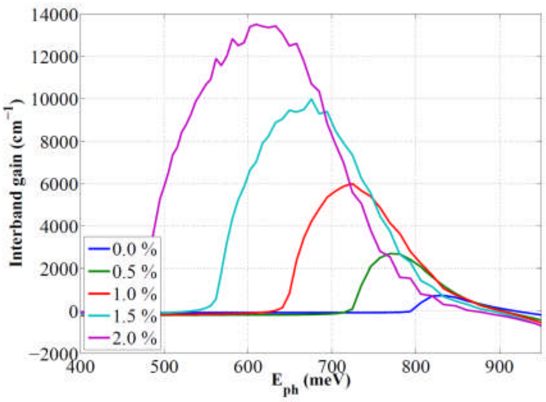

Fig. 2. Interband gain spectra for [001] Ge for a range of biaxial tensile strain levels, with carrier densities $n = p = 5\text{x}10^{18}\text{cm}^{-3}$ and at a temperature of 300K.

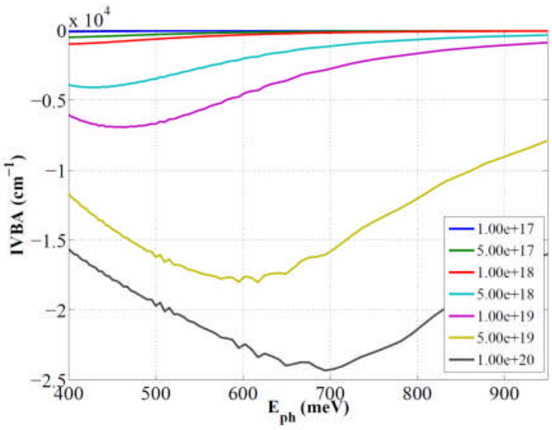

Fig. 3. Intervalence band absorption spectra for [001] Ge with 1% biaxial tensile strain, for a range of hole densities, at 300K.

and only for carefully controlled doping and injection levels. This result is consistent with the experimental analysis of ref. [4]. Whilst carrier injection is required to introduce holes into Γ-point valence states, too high an injection level results in strong IVBA which quenches the net gain. In any case, high n-type doping levels ($5\text{x}10^{19}\text{cm}^{-3}$) are required to achieve sufficient band-filling of the indirect (L) valley states. These quantitative conclusions apply to a lattice temperature of 300K; calculations carried out at 353K – a more realistic estimate of the core device temperature in a Ge laser – show that the laser threshold is more difficult to obtain, with a minimum biaxial tensile strain level of ~1.3% required.

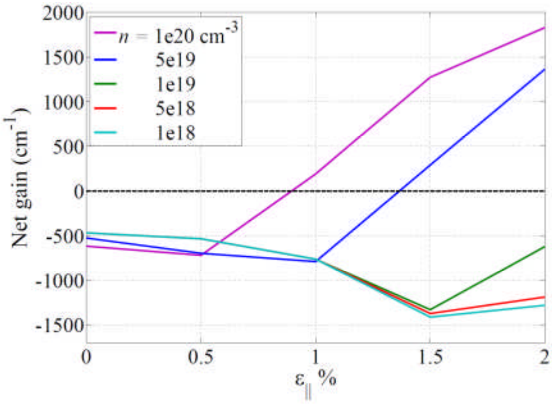

Fig. 4. Peak net gain in [001] Ge (including interband material gain, IVBA and intra-conduction band absorption) as a function of biaxial tensile strain ($\varepsilon_{||}$) for a range of total electron densities (doping + injected carriers) and a fixed injected carrier density of 10^{18}cm^{-3}, at 300K.

ACKNOWLEDGMENTS

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