

# Light emission from strained germanium

## Supplementary information

P. Boucaud,<sup>1, a)</sup> M. El Kurdi,<sup>1</sup> S. Sauvage,<sup>1</sup> M. de Kersauson,<sup>1</sup> A. Ghrib,<sup>1</sup> and X. Checoury<sup>1</sup>

*Institut d'Electronique Fondamentale, CNRS - Univ. Paris-Sud 11, Bâtiment 220,  
91405 Orsay, France*

---

<sup>a)</sup>Electronic mail: [philippe.boucaud@ief.u-psud.fr](mailto:philippe.boucaud@ief.u-psud.fr); <http://pages.ief.u-psud.fr/QDgroup>

This supplementary information gives the details for the radiative recombination calculation applied to the structures described by Jain *et al.*<sup>1</sup> The generalized Planck's law based on the principle of detailed balance allows to predict the luminescence radiation from absorption data for direct or indirect band gap transitions.<sup>2</sup> In semiconductors, the occupation of valence and conduction bands is accounted for by a chemical potential corresponding to the difference of quasi-Fermi energies. This law can predict either thermal or luminescence radiation. The emitted radiation per photon energy interval is proportional to

$$R(\hbar\omega) \propto \frac{\alpha(\hbar\omega)(\hbar\omega)^3}{\exp(\frac{\hbar\omega-\mu}{kT}) - 1} \quad (1)$$

where  $\alpha(\hbar\omega)$  is the absorption and  $\mu$  the chemical potential. For measurements performed with a spectrometer as shown in Ref. 1, this formula has to be modified to account for spectral window in wavelength units. For thermal radiation,  $\mu = 0$ . For photoluminescence,  $\mu = E_{Fe} - E_{Fh}$  where  $E_{Fe}$  is the quasi-Fermi energy for electrons and  $E_{Fh}$  is the quasi-Fermi energy for holes. For a direct band gap recombination, the absorption can be described as  $\alpha(\hbar\omega) \propto \sqrt{\hbar\omega - E_g}(f_v(E_v(\hbar\omega)) - f_c(E_c(\hbar\omega)))$  where  $E_g$  is the band gap energy,  $f_c$  and  $f_v$  the Fermi occupation factors ( $f_c(E_c) = \frac{1}{1+\exp((E_c-E_{Fe})/kT)}$ ),  $\hbar\omega = E_c - E_v$ . The carrier concentrations used to calculate the quasi-Fermi energies are given by the sum of the intrinsic carrier concentration that depends dramatically on the temperature (in bulk semiconductors,  $n_i = \sqrt{N_e N_h} \exp(-E_g/2kT)$  where  $N_e$  and  $N_h$  are the temperature-dependent effective density of states for electrons and holes) and the photo-induced carrier concentration. When tensile strain is applied, the intrinsic carrier concentration is calculated by taking into account the degeneracy lifting in the valence band between heavy holes and light holes. At room temperature, the intrinsic carrier concentration in unstrained germanium is  $2 \times 10^{13} \text{ cm}^{-3}$ . At 550°C, i.e. 525°C temperature increase, the intrinsic carrier concentration of strained germanium is calculated to be  $1.5 \times 10^{18} \text{ cm}^{-3}$ . In the letter by Jain *et al.*, the temperature increase in the membrane follows a linear dependence as a function of the incident pump power with a slope of 35°C/mW, i.e. 350°C at 10 mW (Fig. 5a). Indeed, apart from strain engineering, the MEMS processing decreases the thermal dissipation of germanium. This thermal dissipation depends on the exact geometry of the membranes and varies from samples to samples. The dependence of 35°C/mW is thus just an indicative reference value. We emphasize that thermal dissipation is significantly stronger in bulk germanium substrates

and one does not expect such temperature increase in the bulk substrate used for comparison in Ref. 1. The band gap temperature dependence is taken following the formula given in Ref. 3. The effect of strain is considered as shown in the supplementary figure S8 for a 1% uniaxial strain, i.e. a decrease of the band gap energy, a decrease of  $\Gamma - L$  valley splitting and a degeneracy lifting between heavy holes and light holes. A very important parameter to describe the photoluminescence spectra is the photo-induced carrier density. If the photo-induced carrier density is lower than the intrinsic carrier concentration, the chemical potential is equal to zero and the photoluminescence is equivalent to the thermal radiation. In Ref. 1, Jain *et al.* mention a non-radiative recombination time constant of 1 ns. For simplicity we consider that the carrier concentration is governed by this non-radiative rate, i.e. without accounting for radiative or Auger recombinations. The photo-induced carrier density depends on carrier diffusion along the vertical direction and in the membrane plane. If we consider a volume of  $10 \times 10 \times 0.1 \mu\text{m}^3$  for photo-induced carriers, and if we account for the reflection at 532 nm, the calculated optically-induced carrier density is around  $1.6 \times 10^{18} \text{ cm}^{-3}$  for a 10 mW incident pump power. This value is only indicative as one can expect a large dependence of non-radiative recombination *vs.* incident pump power as the membrane can reach temperatures as high as 500°C. To account for this effect, we have considered for the calculation in Fig. 1 a linear dependence of the carrier concentration as a function of the pump power with a slope value of  $2.5 \times 10^{16} \text{ cm}^{-3}/\text{mW}$ . We also note that the spectra for germanium reported in supplementary Figure S3 are very noisy, and just above the detection limit. Almost no signal is detected below 8 mW. It is an indirect indication that the photo-induced carrier density is not very large in the germanium-on-insulator material, supporting the values of carrier density used in the calculation.

The striking feature reported in Fig. 1 of the comment is the strong superlinear dependence of the calculated emission as a function of the incident power with a threshold around 10 mW. For a temperature increase of 40°C/mW, the calculated power law exponent value for the emission at 1550 nm *vs.* incident pump power is 7.25 in close agreement with the  $m = 7.49$  value reported in Ref. 1. The exponent value depends on the temperature increase in the membrane. A temperature increase of 35°C/mW leads to an exponent value of 6.5, slightly smaller than the one experimentally measured but still in the same range. The exponent of the emission is also dependent on the photo-induced carrier density. The exponent becomes larger as the photo-excited carrier density is reduced. With intrinsic carrier

concentration, i.e. corresponding to a pure thermal emission, the exponent for the emission at 1550 nm is 8. This value decreases as the carrier density increases. The exponent is equal to 5.2 for a photo-excited carrier density of  $5 \times 10^{16} \text{ cm}^{-3}/\text{mW}$ . The exponents are even larger if we consider the integrated emission instead of the photoluminescence at 1550 nm as reported in supplementary Figures 5 and 6 of Ref. 1. If the strain is increased, the band gap energy is reduced as well as the splitting of the  $\Gamma$  and L valleys, and the threshold occurs, as expected, at smaller pump powers.

This modeling based on the generalized Planck law indicates that the results reported in Ref. 1 can be accounted for by the thermal emission of the membranes, which is not surprising since the membranes reach a very high temperature for the investigated pump powers. The exact values of slope and threshold will ultimately depend on the exact temperature increase and photo-induced carrier density, both features being difficult to evaluate experimentally and accurately at very high temperatures. It is nonetheless clear that a very good fit to the data can be obtained with this simple model.

## REFERENCES

- <sup>1</sup>Jain, J. R. *et al.* A micromachining-based technology for enhancing germanium light emission via tensile strain. *Nat Photon* **6**, 398–405 (2012).
- <sup>2</sup>Schick, K., Daub, E., Finkbeiner, S. & Würfel, P. Verification of a generalized Planck law for luminescence radiation from silicon solar cells. *Applied Physics A: Materials Science & Processing* **54**, 109–114 (1992).
- <sup>3</sup><http://www.ioffe.ru/SVA/NSM/Semicond/> .