Light emission from strained germanium

To the editor — We propose an explanation for the observed photoluminescence enhancement recently reported in *Nature Photonics* by Jain *et al.*[1] in suspended germanium-on-insulator membranes. Based on the generalized Planck radiation law, we show that the experimental results can be accounted for by the high-temperature thermal emission of the suspended membranes. The approach described by Jain *et al.* describes a microelectromechanical system technology for enhancing light emission in germanium by employing tensile strain. An abrupt increase of photoluminescence was observed with a threshold power of around 10 mW. Power law exponent values for the increase in luminescence intensity versus incident power of around 7 were measured. The authors provide a model of the membranes' optical properties that predicts a superlinearity factor of 2.4 but fails to account for the experimentally observed values of around 7.

Jain *et al.* mention that the very large exponent and onset of a threshold are "consistent with optical amplification" or "suggest the presence of optical amplification". However, no linewidth reduction of the emission is observed. One of the key factors associated with the proposed technology is that the temperature of the suspended membranes increases dramatically as a function of the incident optical pump power, as shown in Fig. 5a of ref. 1, with a temperature increase of more than 350 °C for an incident power of 10 mW. This huge temperature increase — characteristic of photopumped suspended germanium membranes — explains the superlinear dependence and onset of a threshold for the spontaneous emission. These features can be reproduced by calculating the spontaneous emission spectrum as a function of the incident power from the generalized Planck radiation law. The details of the calculation, based on the parameters provided in ref. 1, are presented in the Supplementary Information accompanying this Correspondence.

Aside from strain engineering, the processing described in ref. 1 leads to a thermal insulation of germanium by decreasing the thermal dissipation. It therefore leads to a dramatic increase in the temperature of the photoexcited suspended membranes. Meanwhile, the intrinsic carrier concentration in bulk semiconductors increases significantly as the temperature is increased. This effect is reinforced by the tensile strain that decreases the semiconductor bandgap. For a temperature increase of 525 °C (optical pump power of around 15 mW), the intrinsic carrier concentration for strained germanium is calculated to be 1.5×10^{18} cm^{-3}. When the photopumped carrier density is in the same range as the intrinsic carrier density, the recombination will be dominated by the thermal emission characteristics. The key point is that the thermal emission of a membrane measured in the 1–2 μm spectral range exhibits a strong power law dependence as a function of the membrane temperature, leading to the onset of a threshold and a high power law exponent value for the luminescence intensity versus incident power.

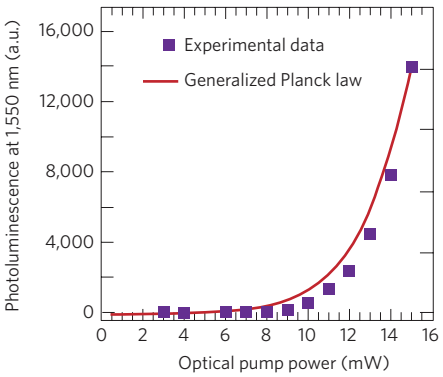

Figure 1 | Experimental photoluminescence data at 1,550 nm reported in Fig. 3 of ref. 1 (squares) compared with emission modelling (solid line) for a 1% uniaxially strained germanium membrane following the generalized Planck law. For the calculation, the temperature increase in the germanium membrane is considered linear, with a slope of 40 °C mW^{-1}. The photoinduced carrier density is also taken to be linear against the incident optical pump power (2.5×10^{16} cm^{-3} mW^{-1}). Note that although the variation of these parameters can modify the threshold and power law exponent values, the trend remains similar. The equivalent power law exponent value *m* is 7.25, as compared to 7.49 in ref. 1.

Figure 1 shows the comparison between the measured data points of ref. 1 and the calculated dependence of the 1,550 nm photoluminescence for the case of a 1% uniaxially strained membrane. The experimental data points correspond to those of Fig. 3 (log–log scale) or Supplementary Information Fig. 7b (linear scale) of ref. 1. Very good agreement is obtained between the model and the experimental data. There is a clear threshold around 10 mW and the exponent value (7.25) is very close to the exponent mentioned in ref. 1 (7.49). These values can obviously be modified depending on the temperature increase and photoinduced carrier density, which can vary from membrane to membrane. We note that when the strain is increased, the bandgap energy decreases, thus leading to a lower threshold as observed experimentally. The striking feature is that thermal emission, not considered in ref. 1, can explain the strong nonlinear dependence of the photoluminescence as a function of incident power. No optical amplification is required — only the temperature increase of the suspended membrane.

This indicates that optical amplification is unlikely to be the driving mechanism for the enhanced photoluminescence. Even though the photoluminescence enhancement seems to be spectacular, the evidence that the elevated temperature and thermal black body emission are the driving mechanisms limits the potential interest of these microelectromechanical-system-type membranes as efficient optical sources integrated on a silicon platform. ❐

References
1. Jain, J. R. *et al. Nature Photon.* **6,** 398–405 (2012).

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Jain *et al.* reply: We appreciate the comments by Boucaud *et al.* on our recent *Nature Photonics* Article[1] and their efforts to develop an explanation of the photoluminescence enhancements observed at high incident optical excitation powers in our tensile-strained suspended germanium-on-insulator devices. Because we were not able in our Article to come to a clear conclusion regarding the mechanism of enhancement at high incident optical excitation powers, this is an interesting