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.

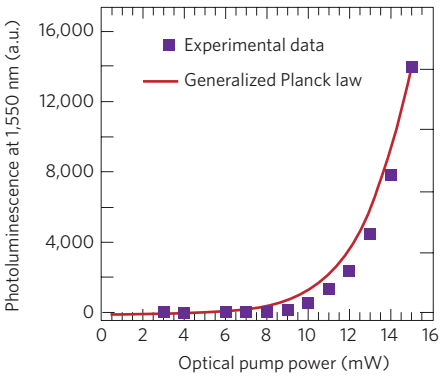

Figure 1 | Experimental photoluminescence data at 1,550 nm reported in Fig. 3 of ref. 1 (squares) compared with emission modelling (solid line) for a 1% uniaxially strained germanium membrane following the generalized Planck law. For the calculation, the temperature increase in the germanium membrane 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
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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

proposal, and the agreement of their model with the form of the relative growth of luminescence at high excitation powers is impressive. When germanium is under tensile strain, the direct bandgap is expected to narrow, which should lead to improved luminescence; the resulting shift in luminescence to smaller photon energies (longer wavelengths) is quite clear in our data, so we remain optimistic about the usefulness of this fabrication approach for the variety of applications we proposed. In light of the proposal by Boucaud *et al.*, we have further examined our calculations and measurements on these structures to see if we can draw definite conclusions about the mechanism of the high-power luminescence behaviour.

In our experiments, as we discussed in our Article[1], there is little doubt that the sample does indeed heat up substantially at high incident optical powers. To understand the influence of temperature on luminescence, we examined the time-dependence of luminescence by partially modulating the excitation laser with an acousto-optic modulator and examining the spectrally integrated luminescence with a photomultiplier. At 3.7 mW, for example, the luminescence increases and decreases in time with the modulation, down to our system-limited resolution of around 200 ns. Because the calculated thermal time constants in our samples (modelled via finite-element analysis in COMSOL) are in the range of hundreds of microseconds, we conclude that the luminescence at such powers is not thermal radiation. At higher powers, in addition to a component of the luminescence that follows the laser modulation, we see both a growth and a subsequent decay in the luminescence with a time constant in the range of hundreds of microseconds, which we therefore presume is associated with heating and cooling. This is qualitatively consistent with the proposal of Boucaud *et al.*, but it is also qualitatively consistent with the luminescence being stronger at higher temperatures because of the relatively larger thermal carrier population of the (direct) Γ valley compared with that of the L valleys. Therefore, although these measurements clearly show thermal phenomena in the luminescence behaviour at higher incident optical powers, our experiments cannot conclusively discriminate between the mechanisms.

Boucaud *et al.* suggest that "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," and we agree that such thermal emission will dominate for intrinsic carrier densities beyond this point. Thermal emission and emission from excited carrier populations are both likely from the same mechanism in this spectral range — namely interband luminescence. The answer to the question of whether the radiation is predominantly 'thermal' or not depends on whether, during the predominant luminescence, the carrier densities in our samples are merely those generated by heating the sample or whether they are larger densities dominated by the direct pumping of carriers into the bands. The carrier lifetime is the key to understanding whether the emission here is predominantly thermal; if it is very short, then the emission is indeed thermal because the populations will relax rapidly to their thermal equilibrium values; if not, then the populations may be much larger than the thermal ones and the emission is not thermal.

The model of Boucaud *et al*. presumes that the photoexcited carrier density is ~2.5×10^{16} cm^{-3} per milliwatt of laser power. For a laser beam of diameter around 5 μm, and presuming that the photoexcited carriers spread uniformly throughout the ~250 nm thickness of the germanium layer after excitation (a presumption that leads to the lowest photocarrier densities), around 5.5×10^{26} cm^{-3} carrier pairs are generated per second per milliwatt of 532 nm incident laser power. Taking the ratio of these numbers gives an effective carrier lifetime presumed by Boucaud *et al.* of around 46 ps. This value is well outside the range of carrier lifetimes reported by others for germanium, which are typically hundreds of microseconds to milliseconds[2–5] at low carrier densities. Our modelling, especially of the Auger recombination (which progressively dominates at high carrier densities in bulk material), predicts effective lifetimes only down to the nanosecond range at the highest densities in our experiments. We acknowledge it is possible that other recombination mechanisms may exist in our samples, such as some surface- or defect-mediated recombination, which might shorten lifetimes to such a degree, although we are not aware of specific measurements of such times in germanium. (Our own measurements of the decay of the luminescence signal were not capable of resolving transients at such short times.) We also note that we do see significant non-thermal luminescence from our samples even at low powers, which would be surprising if there were a non-radiative recombination mechanism as fast as 46 ps.

Even under our most extreme case of 15 mW incident optical pump power (corresponding to a 578 °C maximum steady-state germanium surface temperature modelled using COMSOL), we calculate an intrinsic carrier concentration of 1.687×10^{18} cm^{-3} and a larger optically generated carrier concentration of 6.457×10^{18} cm^{-3}. Our presumption of such longer carrier lifetimes and the consequent dominance of photoexcited carrier densities over thermal ones at all powers is why we presume the thermal radiation would be relatively negligible.

In conclusion, although we have examined our measurements carefully, we cannot experimentally discriminate qualitatively between the thermal luminescence radiation model of Boucaud *et al.* and our own photogenerated carrier luminescence model at high powers. However, we can conclude that the low power luminescence is not thermal. The proposal by Boucaud *et al.* is intriguing and has impressive functional form, although it requires a remarkably short carrier lifetime in the material. ❐

References

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