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D 3.2 Measurement SOA gain spectrum

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Measurement of the SOA gain spectrum

Here we discuss the progress on light amplification in hexagonal silicon-germanium (hex-SiGe) as a gain material. Strong optical amplification has been observed as stimulated emission with a single nanowire as the optical resonator. Using the Hakki-Paoli method the optical gain has been estimated. The observation of net-positive optical amplification in hex-SiGe shows that the material can be used as a base material for a semiconductor optical amplifier (SOA) device.

Optical amplification is the amplification of an optical signal without first needing to convert it to an electrical signal. This can be an outside input (in the case of an optical amplifier) or the light emission of the material itself (in the case of a laser or SLED). Optical amplification is driven by stimulated emission (see Figure 1). To observe optical amplification in a material population inversion of the charge carriers must be achieved. Then when the photons of the optical signal you want to amplify induce stimulated emission an identical photon is emitted, and the optical signal is enhanced.

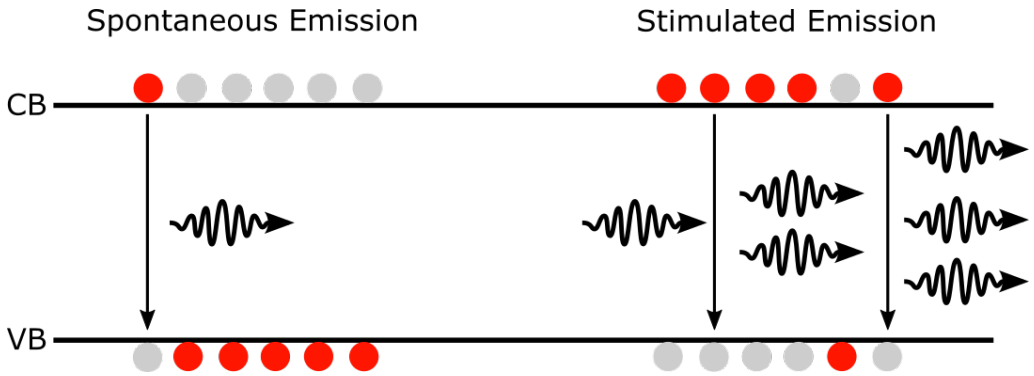

Figure 1. Schematic picture of spontaneous and stimulated emission. The electrons (red circles) fill certain free states, or holes, in the energy bands (grey circles). At low excitation (left) only a few electrons occupy the energy states in the conduction band (CB) and many occupy the valence band (VB). Here mainly spontaneous emission occurs. At very high excitation densities (right), population inversion is achieved. Many more electrons occupy the CB compared to the VB. Now there is a higher likelihood of stimulated emission occurring, where a photon induces an emission of an identical photon. Here it is shown that two such events occur in sequence, creating optical amplification of the initial input light.

We have dispersed hex-SiGe nanowires (with a Ge-content of 80%, and a Si-content of 20%) over an aluminum-nitride (AlN) substrate. The AlN substrate has been chosen for its high thermal conductivity. The nanowires are investigated using optically pumped micro-photoluminescence experiments. The excitation laser is an NKT-ORIGAMI O-10LP with an energy of 1.2eV, a pulse length of <200fs, and a pulse frequency of 40MHz. The excitation laser is focused using a 32x magnification Cassegrain objective to a spot size diameter of approximately 3µm. The photoluminescence (PL) signal is collected using a superconducting-nanowire-single-photon detector (SNSPD) with a high detection efficiency for emission down to 0.54eV. To spectrally resolve the PL signal, a Fourier-transform infrared spectroscopy (FTIR) module is placed before the SNSPD. The resulting spectrum has a minimal spectral resolution of 7 nm (18 cm^{-1}) and can be collected from the signal of a single hex-SiGe nanowire.

To obtain the population inversion needed, high excitation densities are required. This can however increase carrier temperatures due to the excess excitation energy, which can broaden the carrier distribution and reduce the amount of inversion. The high thermal conductivity of the AlN helps by dissipating the heat away from the nanowire. The PL emission from a single hex-$Si_{0.2}Ge_{0.8}$ nanowire at different excitation densities is shown in Fig 2a. At low excitation, there is no resonance in the PL emission observable. At higher excitation densities severable peaks become visible which are attributed to optical modes inside the hex-SiGe nanowire. They are located at about 0.592 eV (green), at 0.613 eV (orange), and at 0.637 eV (red), which is proof of strong optical feedback in the system. To achieve this high amount

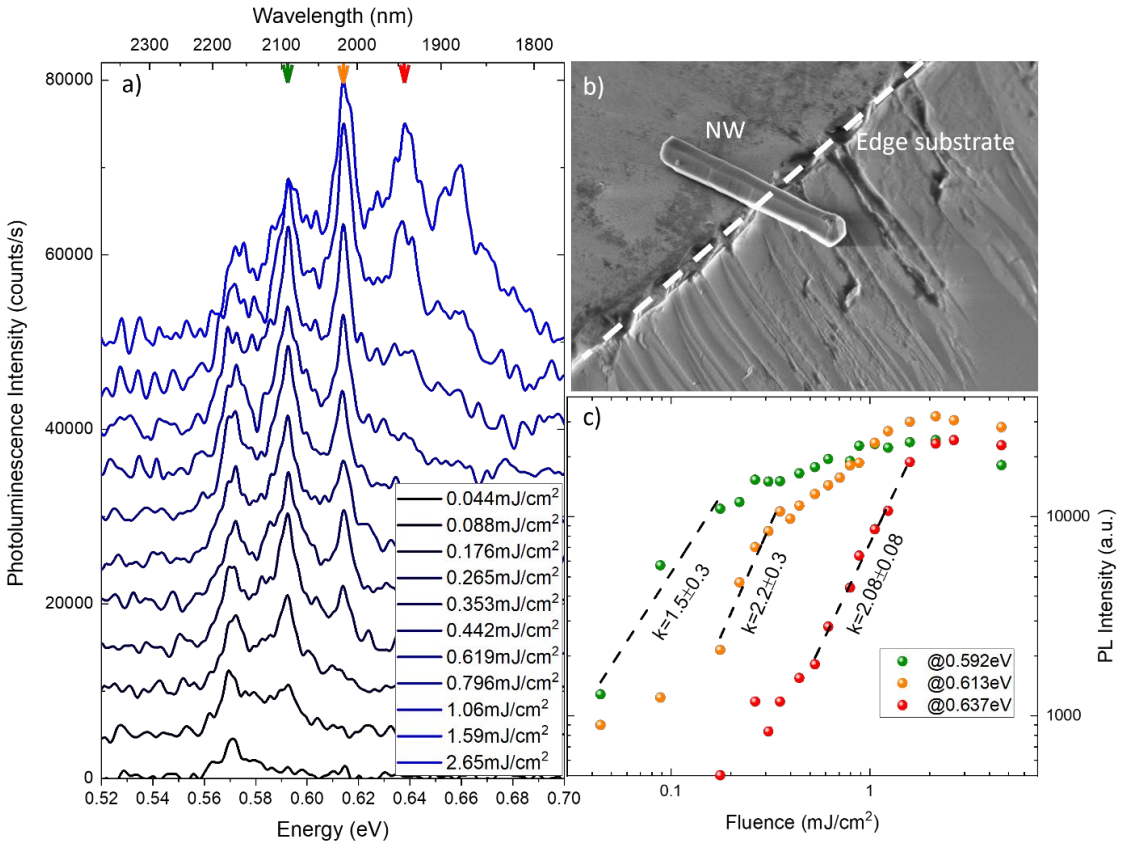

Figure 2 a) The PL spectrum from a single hex-SiGe nanowire partially suspended in vacuum at different excitation densities. Note the resonant peaks which are clearly visible at high excitation density. Different colors indicate peaks which are investigated in further detail. b) SEM image of a hex-SiGe nanowire on the edge of the AlN substrate partially suspended in vacuum. c) PL intensity at the emission energy of the different peaks as function of excitation density. The fitted lines show the power slope during the superlinear behavior of the peaks.

of optical feedback, the reflectivity and the thermal contact are improved by partially suspending the nanowire over the edge of the substrate as shown in Fig 2b. The nanowire end facet which is surrounded by a vacuum has a higher end-facet reflectivity, and the other end on the substrate has a flatter contact area, thus improving the thermal contact with the AlN substrate.

In Fig. 2c the intensities of the different peaks in Fig. 2a are presented as a function of excitation density. A strong S-curve behavior is clearly observed for the intensity of all three peaks. The two higher energy peaks even have a light-in-light-out slope of above a value of 2.0. This strongly indicates optical gain in the system and the presence of dominant stimulated emission [1]–[3].

To check whether the emission is from a single optical mode or multimode, the peak spacing is checked in Fig. 3. In Fig. 3a, the PL spectra fluences are shown as a function of the excitation intensity, where each spectrum is normalized to its maximum intensity. The spectra are plotted as a contour graph where the color scale indicates the excitation intensity. What can be observed from this figure is a shift of the maximum gain in the spectrum to higher energies when the excitation increases. At low excitation the lowest energy peak is dominant, and as the number of carriers in the system is increased and band filling increases, the dominant peak is at higher energy as a result. In Fig. 3b the energy of each peak is shown as function of the excitation density. Here it is clear that the peaks are nearly equally spaced. As a nanowire acts as a Fabry-Perot resonator, each separate optical mode will have an optical mode spacing or Free spectral Range (FSR) given by

$$\Delta E = \frac{hc}{2n_g L}. \tag{1}$$

Where the peak spacing ΔE is dependent on the group refractive index n_g and the cavity length L. The Planck constant h and speed of light c are constants. As we observe a constant spacing, the stimulated emission is likely from a single optical mode.

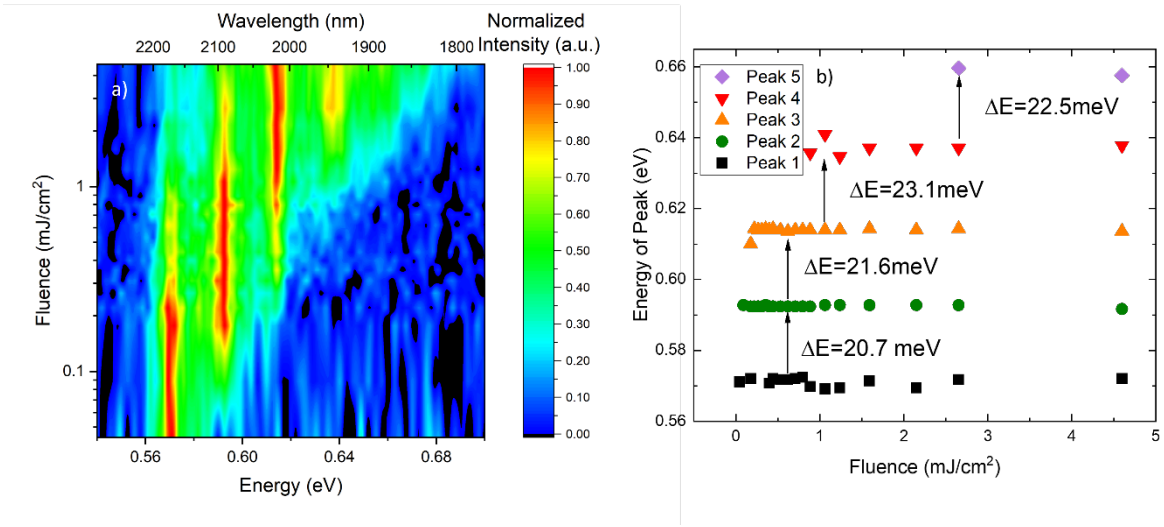

Figure 3 a) Contour graph of the normalized PL spectra at different excitation densities. The color scale indicates the intensity. The spectra at each excitation fluence are normalized to their own maximum intensity. b) Position of maximum intensity for each peak at different excitation fluences. Also indicated is the spacing between adjacent peaks, showing the nearly equally spaced emission.

In Fig. 4 the temperature dependence of the stimulated emission spectrum is shown. In Fig. 4a the emission stays rather constant all the way until about a temperature of 100K. From 6K to 100K the resonances are visible and only slightly decrease in strength compared to the background spontaneous emission. However, above 100K the resonances quickly disappear becoming almost indistinguishable at 220K. This behavior is also shown in Fig. 4b where the total intensity is shown in an Arrhenius plot. The total emission stays constant up until 100K after which the intensity quickly decreases in magnitude. The

temperature dependent emission is fitted using an Arrhenius function where the activation energy for a non-radiative recombination path is found at 73±1 meV. As the total amount of gain is linked to the radiative efficiency of the emission, a decrease in the ratio of peak intensity to background intensity is thus expected. In Fig. 4c the peak energy of the second and third peaks in the spectrum is shown as a function of temperature. A slight redshift of the emission energy is seen as the temperature increases. This is expected, as both the modes shift due to the change in refractive index with temperature and the change in gain spectrum as the bandgap decreases following the Varshni equation [1].

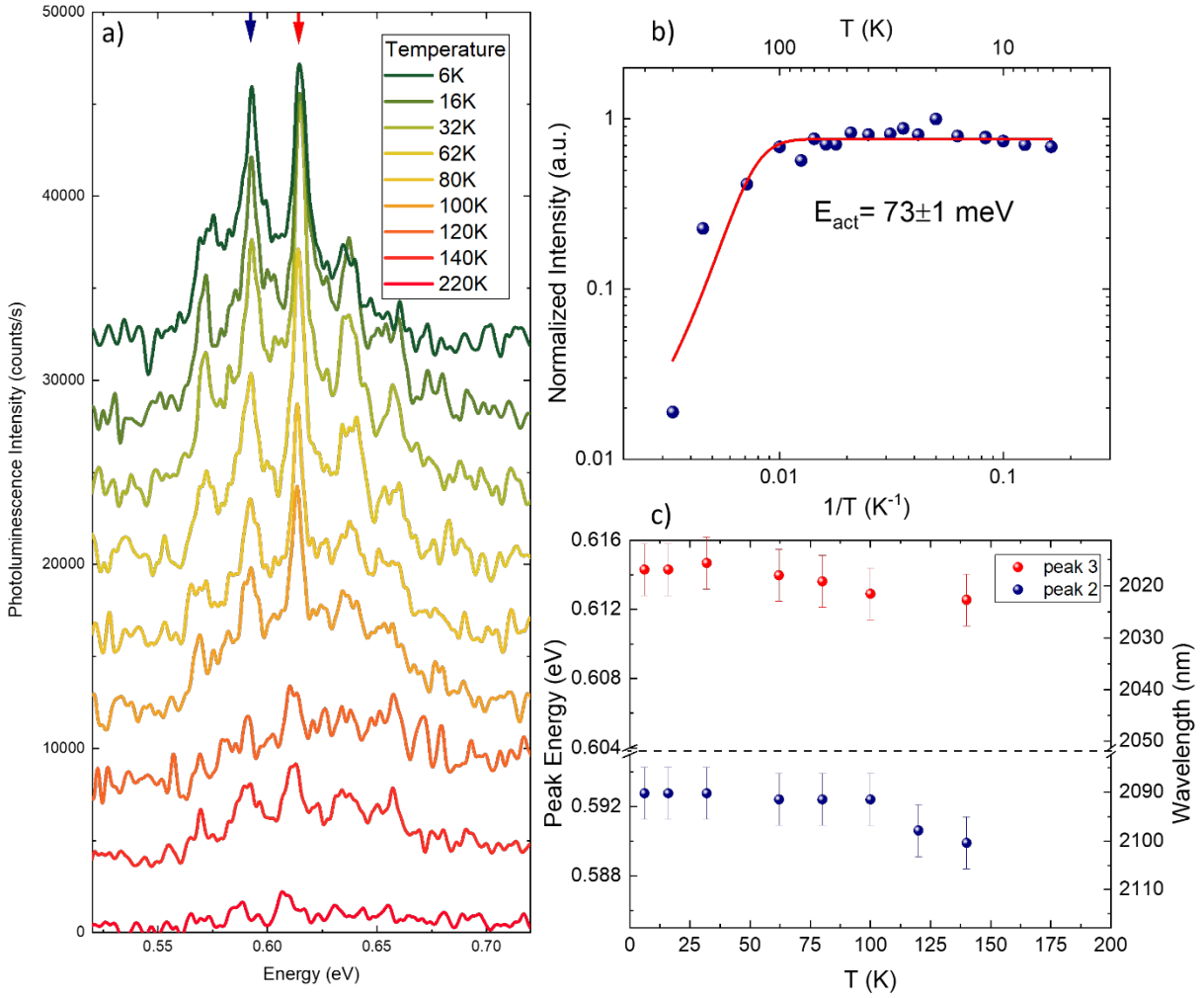

Figure 4 a) The stimulated emission PL spectrum at different temperatures. b) The total PL intensity versus temperature. Data is given in blue, and the Arrhenius fitting function is plotted as a red line. c) The emission energy of the resonance peaks as function of temperature for the second and third peak in the spectrum.

As we observe a resonance spectrum and seem to confirm the emission is from a single optical mode in the nanowire, we can use this to estimate the net optical gain in the material. As our emission seems to be amplified spontaneous emission (ASE), which is stimulated emission below the lasing threshold, we can use the Hakki-Paoli method for estimating the amount of gain. The Hakki-Paoli method is given by [4]–[6]

$$g_{net} = \frac{1}{L}\ln\left(\frac{\sqrt{r}-1}{\sqrt{r}+1}\right) + \alpha_i + \frac{1}{L}\ln\left(\frac{1}{\sqrt{R_1 R_2}}\right). \quad (2)$$

In this method, the net amount of optical gain g_{net} is dependent on the cavity length L, and the reflectivity of both end facets of the nanowire R_1 and R_2. The optical losses per path length α_i, is hard to estimate so is usually set to 0, implying that we can only extract the net amount of gain. The ratio between the peak maximum and the valley is given by $r = \frac{I_{max}}{I_{min}}$, which needs to be evaluated at a single emission energy. As this is not directly possible the two nearest valleys next to an emission peak, $I_{min,1}$ and $I_{min,2}$ are averaged, giving the final equation,

$$r = \frac{2I_{max}}{I_{min,1}+I_{min,2}}. \quad (3)$$

Using Eq. 2 on the observed peaks in Fig 2a indicated in orange, the gain is calculated for different excitation fluences. As the end facet reflectivity's are needed to do this, FDTD simulations have been done to estimate the reflectivity's for both the end facets of the nanowire. As it is hard to determine which mode is visible in the data of Fig. 2 the reflectivity's of both modes are taken as outer estimates.

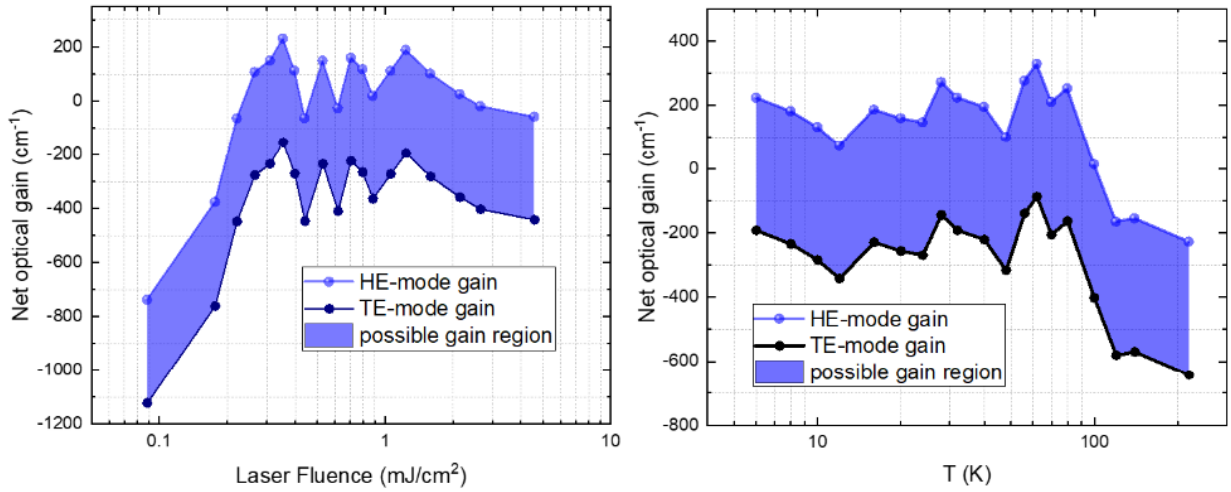

Figure 5 a) Optical gain calculated using the Hakki Paoli method (Eq. 2) from the emission from hex-SiGe. The gain is given if the HE-mode is dominant (blue line) if the TE-mode is dominant (black line) and the possible range if values if both modes are present (shaded area). b) Same optical gain calculation, but now as function of temperature.

In Fig. 5a the net optical gain is shown as a function of excitation fluence. A range of values is given for each fluence, with the lower estimate equating to if the emission is dominated by the first TE mode and the higher estimate when it is dominated by the first two degenerate HE modes. At low excitation densities, the gain is very negative meaning the internal losses are much larger than the gain. However, the gain increases with excitation density becoming net positive around 1mJ/cm^2**.** The gain saturates at a value of g=229 cm^{-1} for the HE modes and g=-152 cm^{-1} for the TE modes. This is a decent value as this means with sufficient population inversion this material can show relatively high optical amplification. However as the gain for the TE mode it is still negative, it is uncertain. This does ignore any optical losses α_i outside of the reflection losses, which can have a major impact. In equation 2 an increased α_i with only increase the real amount of gain observed, so the given gain estimates are lower bounds for the possible values.

In Fig. 5b the temperature dependence of the gain is shown at an excitation density of 1.3 mJ/cm^2. The gain is relatively constant at low temperatures up to 80K. Above this temperature, the gain decreases until it is so low it cannot be extracted from the PL spectra. This behavior can be well understood when compared to the PL intensity as a function of temperature in Fig. 4b. The gain and total PL intensity are correlated as they both start decreasing from the same temperature. The total measured PL intensity is proportional to the number of excited carriers in the system Δn. The gain is proportional to the amount of population inversion, which in turn is directly proportional to Δn. Thus, the decrease in gain observed in Fig. 5b is explained by the reduction of population inversion in the system due to thermal effects.

Overall, net optical gain is observed and is relatively high with lower-bound values reaching g = 229cm^{-1}. This means hex-SiGe can show optical amplification. As the gain is stable up to 80K, the optical amplification can be done up to that temperature without loss of efficiency. This finding is an important step towards the fabrication of hex-SiGe semiconductor optical amplifiers and lasers.

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