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D 4.2 Demonstration of an optically pumped QW laser

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Demonstration of an optically pumped QW laser

Here we will discuss the progress on optically pumped single NW laser of hexagonal Silicon-Germanium (hex-SiGe) . It has been observed that stimulated emission has been reached in the system. By showing this, a first great step towards actual CMOS-compatible nanolasers is achieved.

To observe stimulated emission in our PL measurements, stimulated emission needs to become the dominant recombination method in the system. This regime of dominant stimulated emission is called Amplified Spontaneous Emission (ASE) and will transition into lasing once coherent emission is achieved. To achieve ASE (and thus lasing) the gain threshold needs to be reached

$$\Gamma g_{th} = \alpha - \frac{1}{2L}\ln(R_1 R_2). \qquad (1)$$

Here g_{th} is the gain threshold at which lasing is reached. The overlap of the light with the gain material Γ should be higher than the losses on the righthand side. With α being the optical losses per path length, and $R_{1,2}$ being the reflectivity on each side of the cavity with length L.

From Eq.1 it can be seen that increasing the reflectivity of the end-facets of the resonator ($R_{1,2}$) will lower the threshold needed to observe stimulated emission. Thus, we created an external cavity for the hex-SiGe NWs, called a microstadium resonator, on which the NW can be placed. This is known to enhance the confinement of the light into the gain material [1]. From own simulations the confinement of the light into the nanowire showed an enhancement of a factor 60. A schematic of the microstadium cavity in shown in Fig.1a

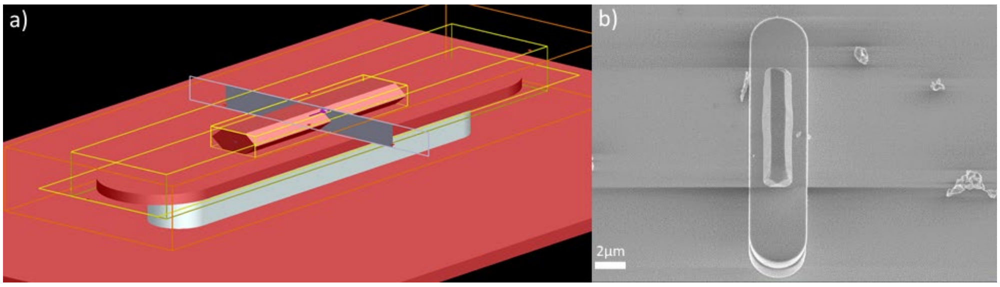

Figure 1 a) Schematic of the NW-microstadium cavity which was used to achieve stimulated emission. b) SEM image of a fabricated NW-microstadium cavity.

Here the wire is put on top of a Silicon stadium, on a silicon-oxide pillar, on top of a silicon substrate. The microstadium resonator is fabricated by etching the structures from basic Silicon-On-Insulator (SOI) wafers. Then the NW is transferred onto the wire using a mechanical transfer tip under optical microscope. In Fig.1b an SEM image of the realized laser structure is shown. Here the NW can clearly be seen lying on top of the stadium in a straight and central orientation. This straight orientation is important for the performance of the external resonator.

There are several experimental methods to verify whether lasing has been reached. To reach lasing carrier population inversion needs to be reached [2][3], which can be done by pumping the system strongly to generate a large amount of excess carriers. We use optical pumping of the system to reach the population inversion condition. By then measuring the emitted PL, stimulated emission and lasing can be confirmed by checking several observations. The first is the superlinear increase of the intensity of the expected lasing mode, which is often called the S-curve [4]. The S-curve is a result of the much higher recombination rate of the stimulated emission compared to the spontaneous radiative recombination rates, with lifetimes usually around 10s of picoseconds instead of nanoseconds [3][5]. This causes most of the light now being emitted in the lasing mode, competing with the spontaneous recombination channel. While the stimulated emission is not fully dominant yet, the intensity will thus start to increase superlinearly with excitation power. Once the stimulated emission is fully dominant, lasing has been reached and the intensity will again scale linearly with excitation power, causing the characteristic S-curve.

During this superlinear increase of the excitation density a narrowing of the emission wavelength is also expected. Lasing only occurs at the wavelengths at which the optical cavity causes constructive optical feedback. These specific wavelengths are determined by the modal structure inside the cavity and the size of the cavity. The most common cavity for nanowire lasers is the Fabry-Perot cavity which will have a constant spacing between the emitted peaks, called the Free Spectral Range (FSR), which is dependent on the length of the cavity, which can be given by in wavelengths

$$\Delta\lambda = \frac{\lambda^2}{2L\left(n - \lambda(dn/d\lambda)\right)}. \tag{2}$$

Where λ is the wavelength, $\Delta\lambda$ is the spacing of the peaks. The refractive index inside the cavity n, and L the length of the cavity, both influence the spacing. Longer cavities cause the peaks to be closer together, thus the design of the cavity has a major influence how many modes will be able to lase.

The linewidth of each of these peaks is determined by the quality of the cavity. This is given by the Q-factor, which says how long the light is contained within the cavity. The longer the light can exist inside the cavity the higher the Q-factor will be, and the narrower the emission peak will be. The Q-factor is given by

$$Q = \frac{E}{\Delta E}, \tag{3}$$

the Q-factor, Q, is given by the energy of the emission peak E, divided by the Full-Width-at-Half-Maximum (FWHM) of the peak in energy scale ΔE. Observing both the S-curve and narrowing of the spectral peak will give a clear proof whether stimulated emission and maybe even true lasing is occurring [6].

Setup

The setup used for the optical characterization of the nanowire stadia was a micro-PL setup, shown in Fig.2. Both Time-Resolved Photoluminescence (TRPL) and spectrally resolved PL are performed on the sample.

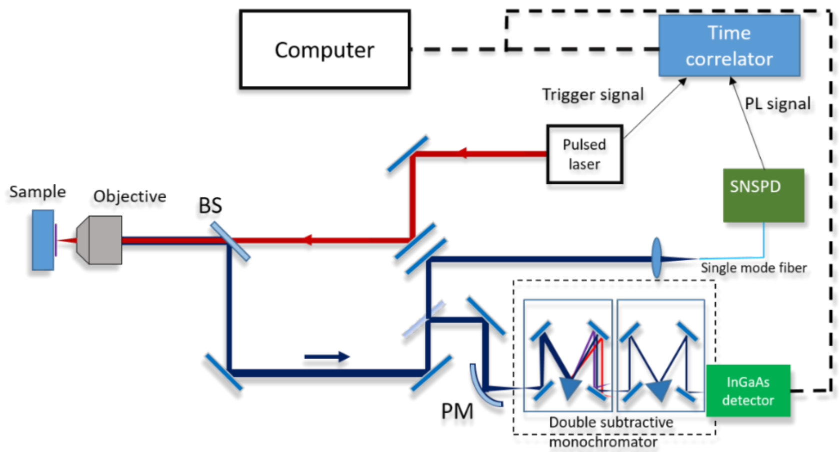

Figure 2 Schematic of the optical setup used for the measurements in this work-package. Both TRPL and spectrally resolved measurements are capable of being done. The pulsed laser excites the nanowires with a wavelength of 1030nm and a repetition rate of 40MHz. It is focused by a 36x objective onto the sample. The emitted PL is collected by the same objective and then measured by either the SNSPD or the InGaAs detector, after passing through a monochromator. The SNSPD and laser are correlated to be able to measure time correlated PL.

The excitation laser is a femtosecond pulsed laser, excitation wavelength 1030nm, with a pulse repetition rate of 40MHz. The laser is focused using a 36x reflective objective to a spotsize of 4μm diameter on the sample. The light is collected with a SNSPD for the TRPL measurements and a thermo-electrically cooled extended InGaAs detector for the spectrally resolved PL measurements.

Experimental results

To proof we see lasing-like emission we will both show superlinear increase of intensity with excitation density in TRPL and linewidth narrowing in spectrally resolved PL. First, we will focus on the results from the TRPL measurements. In Fig.3, TRPL measurements on a NW-microstadium structure are shown. In Fig.3a the intensity as function of delay time is measured with increasing laser excitation density. What can be observed is that for low excitation densities, in black, the decay is mono-

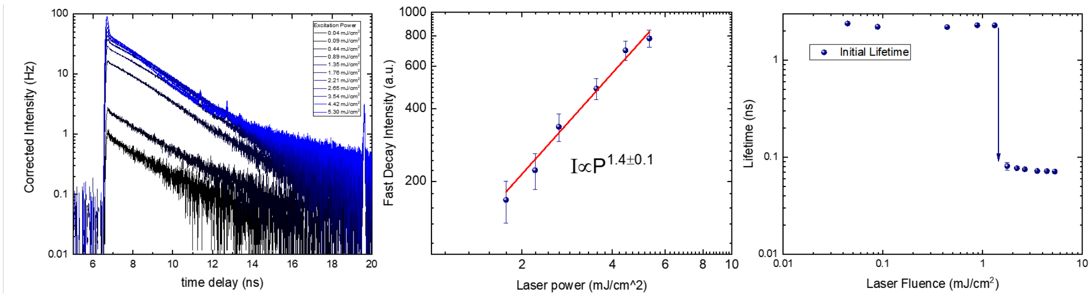

Figure 3 TRPL results from a nanowire-stadium device. (a) Time traces which show carrier recombination rates at different excitation densities. At low excitation densities (in black) a mono-exponential decay is observed, this indicates it is dominated by spontaneous radiative recombination. At higher excitations (in blue) a sharp decay can be seen on top of the spontaneous decay, this is due to stimulated emission which is much faster. This shows the recombination is dominated by lasing-like emission. (b) Intensity of the fast decay as function of the excitation density. The super-linear increase (power-slope of 1.4) shows the recombination becoming more efficient with higher excitations. This is part of the characteristic S-curve. (c) Initial lifetime of the decay as function of the excitation density. The sudden decrease of the lifetime at a threshold is the moment stimulated emission becomes dominant.

exponential and has a slow decay with a lifetime of 2ns. When increasing the excitation density above a laser fluence of $1\mathrm{mJ/cm^2}$ the behavior of the decay changes. Now the decay initially begins with a very fast process, with a lifetime of 72ps, as can be seen in Fig.3c. This is an increase in recombination rate with a factor 30 compared to the decay process dominant at lower excitation densities. As discussed before, this is indicative of stimulated emission recombination being dominant. Furthermore, in Fig.3b, this initial very fast decay has a super-linear relation with the excitation density, as optical excitation density is generally linearly equivalent to the injected carrier density. The fast recombination becomes more efficient as the excitation density increases. The fast decay and the super-linearity of the emission intensity both indicate that stimulated emission is dominant in the initial part of the decay at high excitation densities >1mJ/cm^2. As discussed before, these results clearly indicate the existence of stimulated emission being strong in hex-SiGe[5]. As stimulated emission is the recombination channel which drives lasing in a material, this strongly indicates the obtaining lasing from hex-SiGe is close.

As there is a clear stimulated emission contribution in the emission, the spectral PL was also investigated. For this measurement a double subtractive monochromator was used with an extended-InGaAs detector positioned at the output slit. Again a single hex-SiGe nanowire on a microstadium is

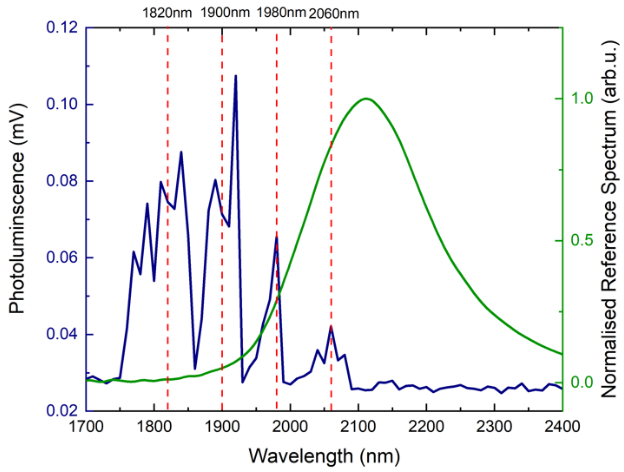

Figure 4 Resonance spectrum of the NW-microstadium cavity in blue. The free spectral range of the peaks is 80nm, with a very strong resonance depth. In green is the PL of an ensemble of NWs of the same sample to show the overlap between the spontaneous emission and the stimulated emission spectrum

measured under similar conditions as the TRPL measurements. At very high excitation densities a spectrum with a clear resonance is observed in figure 4. Compared to the ensemble measurement of several hex-SiGe nanowires at low excitation (in green), the spectrum of the NW-stadium is much more shifted to higher energies and is made up out of several sharp peaks instead of one broad peak. The blue-shift of the spectrum can be explained by the much higher excitation densities in a smaller volume of material. This results in a much higher carrier density and the bandstructure will then be filled up to much higher energies with excess carriers. The peaks of the resonance spectrum are equally spaced with a FSR=80nm with corresponds to an optical path length of 10µm from Eq. 2, which corresponds with the NW length used in the experiment. This means the device shows a Fabry-Pérot resonance with a strong oscillation depth. The FWHM of the peaks are around 45nm using a Lorentzian peak fitting function, which corresponds to a Q-factor from Eq. 3 of $Q \approx 48$. It should be noted that the resolution due to the slit size of the monochromator was 52m, which means the measured resonance peaks where instrument limited, in reality the width of these peaks is likely to be smaller. Thus a higher Q-factor can be expected to have been emitted.

As the intensity still increases super-linearly at the highest excitation densities, it cannot be claimed that the sample has reached lasing, however these are strong indication ASE has been reached. This is the precondition of lasing, where stimulated emission is becoming dominant in the system but full coherent has not been achieved yet. From the resonance of the spectrum in Fig. 4 we can also estimate the effective gain of the hex-SiGe NW-stadium. Using the Hakki-Paoli method the gain of an ASE spectrum can be estimated [7]. The relation given by

$$g = \frac{1}{L} ln\left(\frac{\sqrt{p}-1}{\sqrt{p}+1}\right) + \frac{1}{2L} ln\left(\frac{1}{R_{tot}}\right), \quad (4)$$

shows that the effective gain in the device , g, can be estimated by the modulation depth, $p = \frac{(I_{max}-I_{min})}{(I_{max}+I_{min})}$, and the total facet reflectivity of the cavity for one full round trip of a photon, R_{tot}. By using FDTD simulations to determine the cavity reflections R_{tot}, and using the modulation depths from Fig. 4, the effective gain can be estimated to be in the range of $g \sim 500 \pm 20\ \mathrm{cm}^{-1}$. This is only slightly lower than often reported in other semiconductor lasers, which often have a modal gain around $\sim 1000\mathrm{cm}^{-1}$ [8], thus in terms of modal gain hex-SiGe generates enough gain to have the stimulated emission dominate.

We have observed super-linearity of the PL-intensity with excitation power, picosecond recombination rates above a threshold of 1mJ/cm^2, a resonance spectrum with a strong modulation depth, and a relatively high gain. All of these observations together show that we possibly have reached lasing already, but clear proof is not yet obtained. To fully proof we have lasing we will perform g(2) photon-autocorrelation measurements, which can proof whether the emission is chaotic or coherent [9]. This will definitively determine whether the emission is dominated by lasing or spontaneous emission.

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