Silicon Photonics
矽光子學
Prospects for Silicon Light-emitting Devices (B)

課程編號：**941 U0460**

科目名稱：矽光子學

授課教師：黃鼎偉

時間地點：一**678** 明達館 **303**

DISLOCATION-ENGINEERED EMITTERS

- During the anneal step, displaced silicon atoms, substituted for boron atoms, form dislocation loops at the end of the implanted ion range.
- The concentration and distribution of the loops is dependent on both the implanted ion dose and the subsequent thermal processing.
- Device fabrication is completed with front- and back-side wafer metallization, with patterned windows allowing the escape of light.
- A schematic of the device is shown in Figure 8.19 together with the current/voltage characteristic.
- These data provide clear evidence that these devices exhibit excellent electrical performance, as one would expect from a process that is used routinely in the fabrication of *p-n* junctions in mainstream silicon device manufacture.
- This is a signifi-cant advantage over those technologies dependent on a highly resistive optically active medium because it ensures efficient carrier injection.

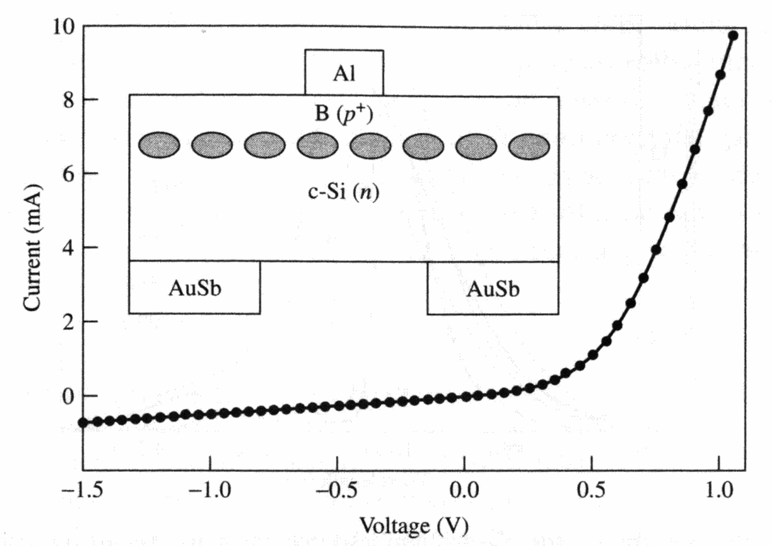

Figure 8.19 Current/voltage plot for a dislocation-engineered Si LED measured at room temperature. The light is emitted through the bottom contact window.

DISLOCATION-ENGINEERED EMITTERS

- Figure 8.20 shows the EL spectra of this silicon LED.
- Unlike the (Er + O)-doped Si LEDs, described in section 8.1.4 these devices are driven by a forward bias current.
- The most striking feature is the apparent increase in total integrated power as the temperature of device operation is raised towards 300 K.
- This complete lack of temperature quenching was attributed solely to the confinement of the excited carriers and the subsequent prevention of nonradiative recombination via lattice defects.

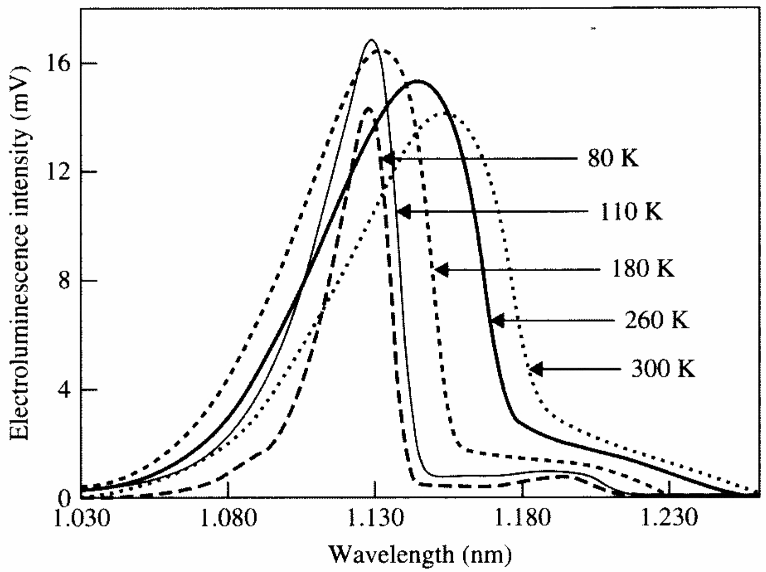

Figure 8.20 Spectra of the electroluminescence intensity versus wavelength at various temperatures. The device was operated at a forward current of 50 mA for all temperatures.

DISLOCATION-ENGINEERED EMITTERS

- In a later publication, the same group explored the co-doping of these dislocation-engineered LEDs with Er and beta-phase iron disilicide (β-$FeSi_2$) [24].
- The expressed aim was to fabricate LEDs with emission at a wavelength in the region of 1.5 μm.
- Although the authors conceded that the co-doping process was far from optimized, they demonstrated room-temperature EL at a wavelength of approximately 1.55 μm for both Er and β-$FeSi_2$ samples.
- Control samples which were free from dislocation loops failed to yield any such EL, thus confirming the partial elimination of temperature quenching.

DISLOCATION-ENGINEERED EMITTERS

- The potential application and widespread deployment of the dislocation-engineered Si LEDs provides an interesting footnote to the search for an efficient silicon light source.
- The fabrication processes use implantation and anneal recipes which are common in the silicon microelectronics industry.
- It is likely, then, that tens of millions of dislocation-engineered Si LEDs have in fact been fabricated in the last few decades and are operating in integrated circuits worldwide.

8.4 RAMAN EXCITATION

RAMAN EXCITATION

- We have thus far concentrated on the search for material systems exhibiting efficient electroluminescence for the fabrication of silicon-based LED and laser sources.
- There also exists a requirement for silicon waveguide optical amplifiers which can perform the same function as an EDFA (see section 8.1) but with a much smaller geometry (approximately 1 cm or less as opposed to tens of meters for doped fiber amplifiers).
- Such devices could be used as stand-alone optical amplifiers or, if integrated with silicon photonic components on the same chip, could result in loss less device operation (i.e. the on-chip amplification balancing fiber to chip coupling and waveguide propagation losses).
- In addition to potential and demonstrated (in the case of Si nano-crystals) gain mechanisms outlined in this chapter, a promising approach is the use of the Raman effect, a potentially straightforward solution which requires no additional device processing above that necessary to fabricate the silicon waveguide.

Spontaneous Raman Effect

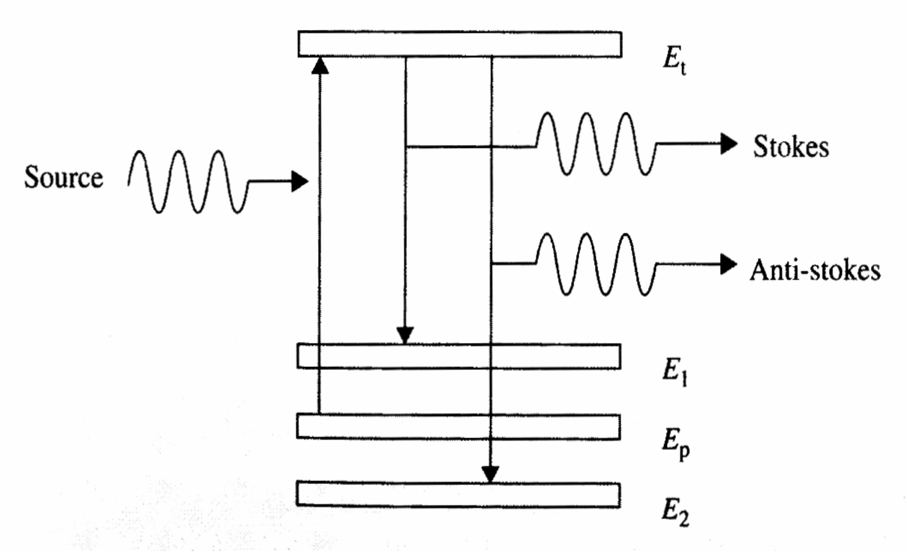

Figure 8.21 Diagram of the spontaneous Raman effect

Spontaneous Raman Effect

- The spontaneous Raman effect is a very well known and documented phenomenon covered in a number of textbooks (for example see [25]).
- It is manifested in the observation of faint sidebands in the frequency spectrum when (almost) monochromatic light scatters from a solid material.
- The frequency difference between the sidebands and the input power is always fixed and dependent on the make-up of the scattering medium.
- This can be explained via the transient absorption of the incident photons. In the case of an optical source in the near-infrared (as is generally the case in optical communications) with a wavelength of 1-10 μm, photon absorption can occur via the excitation of molecular or atomic vibrations of the surrounding medium.
- This is shown diagrammatically in Figure 8.2l.

Spontaneous Raman Effect

- The initial vibrational state of the molecules or atoms making up the medium is E_p.
- Upon absorption of an incident photon the system energy is raised to a temporary level E_t until it relaxes to a state E_1, releasing a photon of energy $E_t - E_1$.
- The excess energy $(E_p - E_1)$ is given up to the system as heat.
- The transition from E_t to E_1 is known as a *Stokes transition.*
- A transition to a level less than E_p (in the above case, E_2), with the subsequent emission of a photon with energy $E_t - E_2$, is known as an *anti-Stokes transition.*
- Therefore, when the frequency spectrum of the scattered light is measured, in addition to the strong signal corresponding to the frequency of the incident light, the Stokes and anti-Stokes transitions result in fixed sidebands synonymous with the Raman effect.

Stimulated Raman Effect

- It is possible to create stimulated Raman scattering (with emission of a coherent light beam) by irradiating a solid with two beams simultaneously, one which excites (or pumps) the constituent molecules or atoms and a second with a wavelength resonant with the Stokes transition.
- This is shown diagrammatically in Figure 8.22.
- In this case, the Stokes transition is stimulated by the signal beam and hence amplification of the signal at an energy of $E_t - E_1$ is observed.
- Unlike conventional semiconductor laser operation, the amplified wavelength is determined by a combination of the pump wavelength and the energy difference $(E_1 - E_p)$, in turn dependent on the scattering medium.
- The stimulated Raman effect therefore opens the possibility for amplification at a wide range of wavelengths extending from the ultraviolet to the infrared.

Stimulated Raman Effect

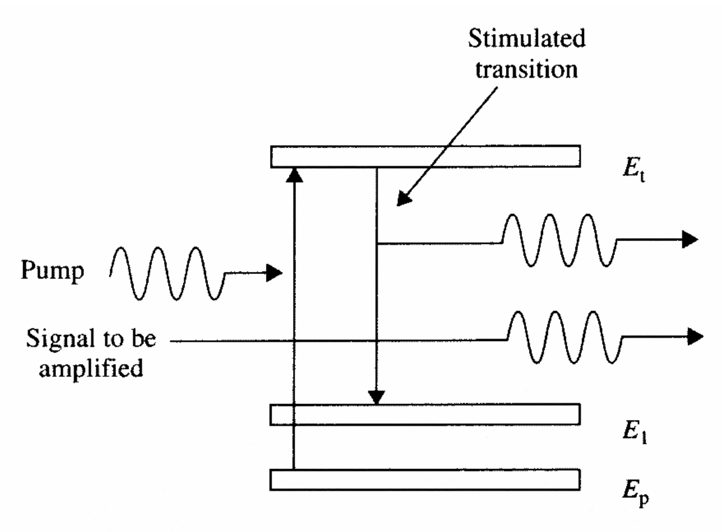

Figure 8.22 Diagram of the stimulated Raman effect

Raman Emission from Silicon Waveguides at 1.54 μm

- The flexibility of wavelength selection for Raman emission makes it an attractive proposition for integration with silicon waveguide technology.
- Recent experimental observation of spontaneous Raman emission from silicon waveguides was reported by the group lead by Jalali at UCLA [26].
- A 1.43 μm pumping source was coupled into a silicon-on-SiO_2 rib waveguide structure with a cross-section of approximately 20 μm^2.
- The Raman spectra were measured for emission from both end facets of the waveguide.
- The results for the forward emission (i.e. for light emitted from the opposite end of the waveguide from which the pump signal was introduced) is shown in Figure 8.23.
- The 1.43 μm pump results in an emission centered at 1.542 μm which varies linearly with the pumping power.
- The spectral width of the frequency of the emitted light is 105 GHz. The Raman scattering efficiency for silicon was deduced as 4.1 x 10^{-7} $cm^{-1} \cdot Sr^{-1}$.

Raman Emission from Silicon

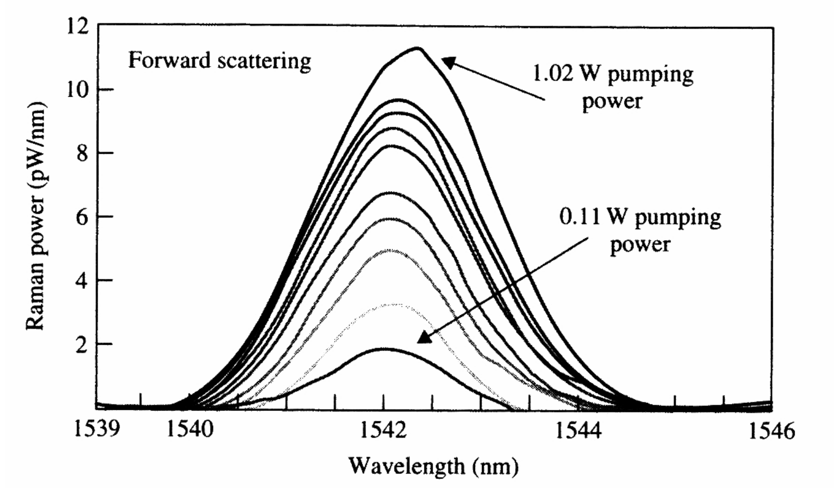

Figure 8.23 Spontaneous Raman spectra measured for different 1.43 μm pumping powers. The greatest intensity shown is for a pumping power of 1.02 W; the least is for 0.11 W.

Raman Emission from Silicon Waveguides at 1.54 μm

- In a subsequent publication the same group examined the feasibility of forming a waveguide amplifier using Raman scattering [27].
- Using a stimulated gain coefficient of 0.07 cm/MW and accounting for coupling and propagation losses and pump and signal mode mismatch, they determined that a pumping power of around 500 m W at 1.432 μm is required to provide a signal gain of 10 dB for a wavelength of 1.54 μm in a waveguide of 2 cm in length.
- A disadvantage of this method for the fabrication of amplifiers is the high power density introduced into the waveguide geometry, which induces nonlinear absorption effects such as two-photon absorption and amplified spontaneous emission.

8.5 SUMMARY

SUMMARY

- In the first seven chapters we provided an introduction to the field of silicon photonic circuits, but this chapter has offered a glimpse of the future, in one of the many exciting research fields currently associated with silicon photonics.
- The aim has been to describe work, currently in progress, towards the development of an efficient, silicon-based, light-emitting device operating at wavelengths suitable for use in communication networks.
- The various approaches described here do not represent an exhaustive list.
- Most notably, a number of devices incor-porating SiGe have been excluded and the reader is referred elsewhere for a description of these approaches [1].
- Rather, we have highlighted those technologies which hold greatest promise from the viewpoint of desired functionality and device integration while using techniques for fabrication which are commonplace in a modern silicon fabrication plant.

SUMMARY

- An efficient silicon light-emitting device (and more significantly a silicon-based laser) is the missing piece in the silicon photonics puzzle.
- Its development would revolutionize the optoelectronics and micro-electronics industries.
- Although significant strides have been taken to achieve that dream we are still many years from its realization.
- Even the most efficient devices demonstrated to date require unreasonable amounts of power, while device reliability remains an issue.
- Significant improvements in device performance are required before widespread use becomes feasible.
- However, the optimist would point to the immense financial rewards that would accompany such a technological development.
- In our opinion this has already created a critical mass that will eventually result in the development of optical sources that will in turn promote silicon as the leading semiconductor material in the photonics industry.