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Theoretical study about the gain in indirect bandgap semiconductor optical cavities

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ABSTRACT

Indirect bandgap semiconductors such as silicon are not efficient light emitters because a phonon with a high momentum is required to transfer an electron from the conduction to the valence band. In a recent study (M.J. Chen et al., 2006) [6] an analytical expression of the optical gain in bulk indirect bandgap semiconductors was obtained. The main conclusion was that the free-carrier absorption was much higher than the optical gain at ambient temperature, which prevents lasing. In this work, we consider the case in which the semiconductor material is engineered to form an optical cavity characterized by a certain Purcell factor. We conclude that although the optical gain is increased, losses due to free carriers increase in the same way so lasing is also prevented even when creating a high-Q optical cavity.

1. Introduction

Silicon photonics has boomed in the last few years as a promising way to create low-cost, high-speed optical interconnects that replace copper wires in future computers [1–3]. The main advantage of using silicon as a photonic material is that it can be processed in microelectronics foundries with high yield and low cost. However, silicon has a main drawback: it is an indirect bandgap semiconductor in which radiative transitions are unlikely and, as so, a very inefficient light emitter. A silicon laser would allow monolithic integration of photonics and electronics on a same chip [2]. Despite huge research efforts by many groups around the world, an electrically pumped room-temperature silicon laser – perhaps the most pursued challenge within photonics – remains elusive.

Bulk crystalline silicon has an indirect energy bandgap so emission of light requires the participation of phonons with the right momentum in order to satisfy the momentum conservation. The low probability of the phonon-mediated radiative recombination process makes silicon a highly inefficient light source. In fact, there exists a general belief that optical gain and thus laser operation in indirect bandgap semiconductors are not possible because the small optical gain – which could be achieved in principle via band–band transitions mediated by phonons – will always be overcompensated by free carrier absorption, regardless of the excitation conditions [4]. This statement, together with the fact that no silicon lasing at room temperature has been reported yet, explains why typically III–V semiconductors having a direct band gap has been used to implement lasers in the near-infrared regime (such as the important optical communications band at wavelength about 1550 nm).

However, some recent theoretical works analyzing the possibility of achieving optical gain in indirect bandgap semiconductors at room temperature have given rise to certain controversy. For instance, Trupke and co-workers suggested that optical gain in silicon is theoretically possible and pointed out that the most suitable energy region is the sub-bandgap region (near infrared) where processes involving phonons could help in achieving gain [5]. Moreover, they obtained that indirect optical transitions can provide negative absorption, i.e., optical gain without an electronic population inversion, but with the assistance of proper phonons. These theoretical arguments were also supported in Ref. [6] where an analytical expression for optical gain via phonon-assisted optical transitions in indirect bandgap semiconductors is presented. The magnitude of optical gain in bulk crystalline silicon is calculated and shown to be smaller than the free carrier absorption at room temperature. However, it is shown, for the first time, that the optical gain is greater than the free carrier absorption in bulk crystalline silicon at the temperature below 23 K [6].

Other some experimental works have reported an increased photoluminescence from silicon when photonic cavities with high

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Q-factor are created Ref(s). [7–15]. In this case, the generation of photons is enhanced in comparison to the case of bulk silicon [16] because of the Purcell effect [17] (or, in other works, the increase of the optical density of states inside the cavity). However, those results have been mainly attributed to an increase of the spontaneous emission rate but nor lasing neither optical gain have been directly observed. So the natural question that arises is can optical gain at room temperature be obtained in indirect bandgap semiconductors when an optical cavity instead of a bulk material is considered? In this work we try to answer this question by starting from the analytical results obtained in Ref. [6].

2. Rate equations

Fig. 1 shows a schematic diagram that describes all possible optical transitions taking place in an indirect bandgap semiconductor such as silicon. It can be seen how three different kinds of particles are involved in this process: electrons, photons and phonons (which are not involved in the same process when taking place in direct bandgap semiconductors).

In Ref. [6], M.J. Chen and co-workers obtained a theoretical expression for the different transition rates that occur in bulk indirect bandgap semiconductors. For the sake of clarity, we represent here the expression of these rates:

$$R_{sp} = M(n_q+1)\cdot NP \tag{1}$$

$$R_{st} = M\cdot n_p(n_q+1)\cdot NP \tag{2}$$

$$R_{ab} = M\cdot n_p n_q\cdot NP\exp\left(\frac{(\hbar\omega+\hbar\Omega-\Delta F)}{K_BT}\right) \tag{3}$$

$$M = \frac{\pi}{8}B_{sp}(\hbar\omega+\hbar\Omega-E_g)^2\exp\left(-\frac{(\hbar\omega+\hbar\Omega-E_g)}{K_BT}\right) \tag{4}$$

In Eqs. (1)–(4), R_{sp} is the spontaneous emission rate, R_{st} is the stimulated emission rate, R_{st} is the absorption rate, n_p is the photon occupation number, n_q is the phonon occupation number, $\hbar\omega$ is the photon energy, $\hbar\Omega$ is the phonon energy, ΔF is the difference between the quasi-Fermi levels for electrons and holes, N is the electron concentration, P is hole concentration (in our study we consider that $N{=}P$), E_g is the indirect bandgap energy, K_B is the Boltzman constant and T is the temperature (we assume room temperature throughout this work). In this work we consider silicon as an indirect bandgap semiconductor, so the

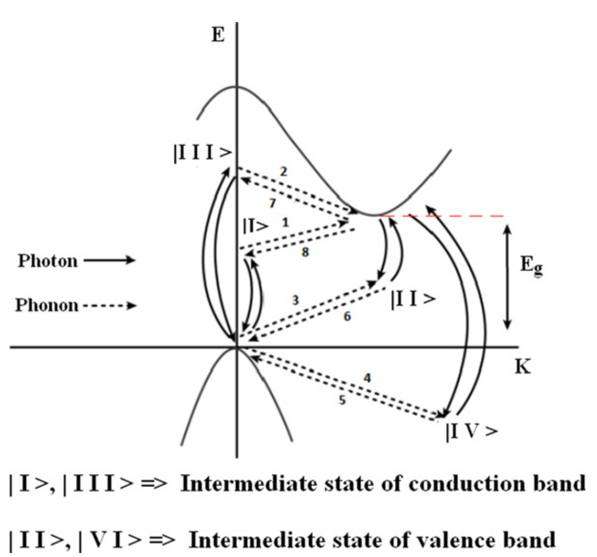

Fig. 1. Schematic diagram of all possible optical transitions in an indirect bandgap semiconductor.

Table 1
Summary of theoretical expression for the carrier, photon and phonon densities.

	Below threshold	Above threshold
Carrier density	$N=\frac{\tau_{c,B}}{F_P}R_p$	$N=\sqrt{\frac{K_{p,b}}{\tau_{p,B}F_PM_B(n_{q0}+1+\frac{\tau_qR_p}{K_q})}}\equiv N_{th}$
Photon density	$N_p\approx M_B\tau_{c,B}^2\tau_{p,B}(n_{q0}+1)R_p^2$	$N_p{=}F_p\tau_{p,B}(R_p-R_{th})$
Phonon density	$N_q\approx N_{q0}$	$N_q\approx N_{q0}+\tau_qR_p$

Final expressions for Np, Nq and N in the photonic cavity.

radiative transition rates can be calculated using the Eq(s). (1)–(4) and the values given in the Table 1 in Ref. [6]. We also consider all the assumptions made in Ref. [6].

The following equations system[1] [6] governs the temporal variation of the photon density (N_p), the phonon density (N_q) and the carrier density (N):

$$\frac{dN}{dt} = R_p-R_{st,B}(\hbar\omega)+R_{ab,B}(\hbar\omega)-R_{sp,B}(\hbar\omega)-\frac{N}{\tau_c} \tag{5a}$$

$$\frac{dN_p}{dt} = R_{st,B}(\hbar\omega)-R_{ab,B}(\hbar\omega)+\beta R_{sp,B}(\hbar\omega)-\frac{N_p}{\tau_p} \tag{5b}$$

$$\frac{dN_q}{dt} = R_{st,B}(\hbar\omega)-R_{ab,B}(\hbar\omega)+R_{sp,B}(\hbar\omega)-\frac{N_q-N_{q0}}{\tau_q} \tag{5c}$$

where Rp is the pumping rate by current injection or optical excitation, β is the spontaneous emission factor representing the fraction of spontaneous emission entering the optical mode that has been considered, N_{q0} is the phonon density at thermodynamic equilibrium and τc, τp and τq are the lifetime of carriers, photons and phonons, respectively. The losses of photons due to the effects such as optical scattering or free carrier absorption can be characterized by a photon lifetime τ_p [6]. The loss of phonons (last term of Eq. (5c)), which represent the anharmonic phonon interaction, can be characterized by a phonon lifetime τ_q [6]. The recombination lifetime of carriers is given by $1/\tau_C{=}1/\tau_{C,RAD}+1/\tau_{C,NRAD}{=}1/\tau_{C,RAD}+1/\tau_{C,SRH}+1/\tau_{C,Auger}$. In Ref. [6], it is assumed that the non-radiative recombination rate is determined by the non-radiative Shockley–Read–Hall (SRH) mechanism. However, in the case of a very high carrier density in silicon, the Auger recombination lifetime is the dominant recombination mechanism, so $1/\tau_{C,SRH}\ll 1/\tau_{C,Auger}$, [18–20]. Considering the above and taking into account the carrier density that we consider in this work ($\sim 10^{19}\,\mathrm{cm}^{-3}$) then we get $\tau_{C,RAD}{=}10^{-4}$ and $\tau_{C,NRAD}{=}10^{-7}$ in bulk silicon.

3. Increase of the optical gain with Purcell factor.

The system of Eq. (5) was solved in [6] for bulk silicon. In this work we have solved the same system but considering a photonic cavity characterized by a quality factor (Q), a modal volume (V_0) and Purcell factor (F_p). These three parameters are related to each other by the following equation [17]:

$$F_P = \frac{3Q(\lambda/n)^3}{4\pi^2V_0}, \tag{6}$$

where λ is the resonant wavelength of the cavity and n its refractive index. It has to be mentioned that we consider that the cavity only affects the photonic density of states by means of F_P but it has no effect on the statistics of the phonons involved in the emission process. This is a good assumption taking into account that the wavelength of the phonons involved in the emission process is much smaller than the optical cavity size

[1] The subscript B stands for the different rates in bulk silicon.