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Modelling of real space transfer optical emitters

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In this paper we report on numerical modelling and optimisation of a novel heterojunction optical light emitter based on longitudinal transport of the electrons and holes. The real-space-transfer of the carriers into the quantum well takes place due to variation of the reverse and forward biased regions with applied longitudinal bias. We show that by altering individual features of the device we can achieve an increase in optical power of nearly 430 times that of the original device.

1 Introduction

The Top Hat Devices (THDs) studied in this paper are variants of Real-Space-Transfer (RST) devices [1]. In the RST heterostructures, with high electric fields applied the electron transfer takes place normal to the field direction between different spatial regions instead of transfer in momentum space. Initial research into the RST devices was focused on electronic functions such as Negative Differential Resistance (NDR), making it an analogue of the Gunn-type diodes. Further development of these devices was aimed at optoelectronic applications [2]. When compared to conventional emitters, the RST-based active optical devices may provide several technological and functional advantages such as design simplicity and potential for monolithic integration of components with various functionality, e.g. emitters and wavelength converters. Since the carrier injection in these devices takes place in the direction normal to current flow, the device operation does not depend on the external bias polarity. This feature is of particular interest for realisation of novel VCSEL-type emitters in which the current does not flow through the DBR mirrors. The latter is a serious problem in traditional VCSEL heterostructures due to mirror damage via electrical heating. The main drawback of the RST emitters is the low optical output power achieved so far. In this paper we present the results of advanced numerical modelling of AlGaAs/GaAs THDs for optoelectronic applications using commercial simulation tool DESSIS [3]. The main task is to optimise the device design in order to substantially increase generated optical power.

2 Device operation

The THD and its mode of operation are shown in Fig. 1. It is a four-terminal device. The top section contains a GaAs quantum well (QW). In normal operation a voltage is applied to contacts 1 and 2 (contacts 3 and 4 are grounded), which accelerates the electrons and holes in their respective channels. The difference in the length between the p-channel and n-channel causes a transverse voltage difference across the junction, which is proportional to the difference in the quasi-Fermi levels (QFLs) of the majority carriers in each channel. As can be seen from Fig. 1a and b, in the spatial region from AA′ to BB′ the QFL in the n-channel is lower than in the p-channel, resulting in a progressively decreasing region of

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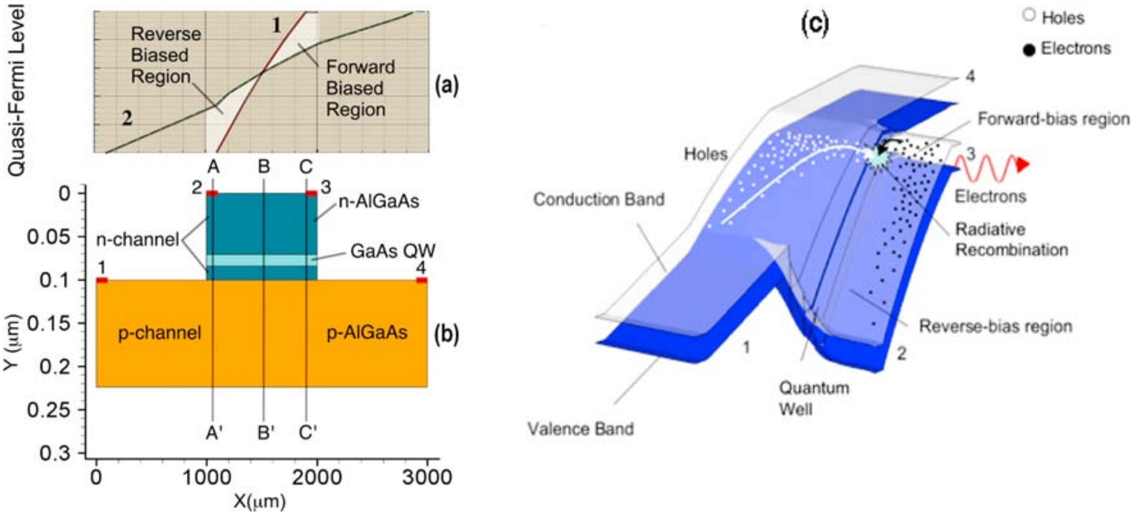

Fig. 1 (online colour at: www.pss-a.com) QFL profiles (a) along the n-channel (curve 1) and the p-channel (curve 2), schematic diagram of THD (b) and its operation principle (c). Due to different length of the n- and p-channels, when the same voltage is applied between the contacts 1 and 4, and 2 and 3, it results in different gradient of the conduction band edges and the corresponding QFLs along each channel, as shown in (a). The interception of curves 1 and 2 means that there exist reverse- and forward-biased regions across the channels on different sides of the intercept.

reverse-bias. In the plane BB′, the QFLs are equal so there is no voltage in this plane across the junction, while in the region from BB′ to CC′ the QFL in the p-channel is lower than that in the n-channel. Thus in this region the junction becomes progressively more forward biased.

When the transverse voltage difference across the junction in the forward bias region becomes large enough to overcome the built-in voltage across the junction, electrons and holes flow into the quantum well, as is shown in Fig. 1c. The operation of the device as a light emitter hinges on the injection of both electrons and holes into the quantum well where they recombine emitting optical radiation. Since the radiative recombination depends on both electron and hole densities it is mainly limited by the carrier type with the lowest density. It is important to note that in our THD the RST takes place solely due to the change of the sign of the transverse bias along the channels rather than due to hot-electron effects [1].

3 Simulation model and results

For numerical simulation we use the standard drift-diffusion model [3], which does not include hot-electron effects, so that the only high-field effect present is the field-dependent mobility. This approach is different from the usual treatment of RST transport when hot electrons play a crucial role. However, in our case the carrier transfer from one region of the device to another takes place mainly due to two-dimensional modification of the energy band profiles under external bias. As a result at least one type of carrier, electrons or holes, are transferred from the bulk barrier region into the QW without appreciable heating. In order to prove that hot-electron effects do not play an important role in our device, we also carried out the simulation using the hydrodynamic model [3], which does include hot-electron effects using the electron and hole temperature approximation. The results of both drift-diffusion and hydrodynamic modelling were practically the same, but the computation time is considerably longer in case of the latter; this explains our choice of the former. In the initial design the QW was placed in the depletion region of the n-channel, as shown in Fig. 1b.

Figure 2 shows the simulated distributions of the energy bands, QFLs and the electron and hole densities in the reverse (Fig. 2a) and forward (Fig. 2b) biased regions at applied voltage of 3 V. The electron–

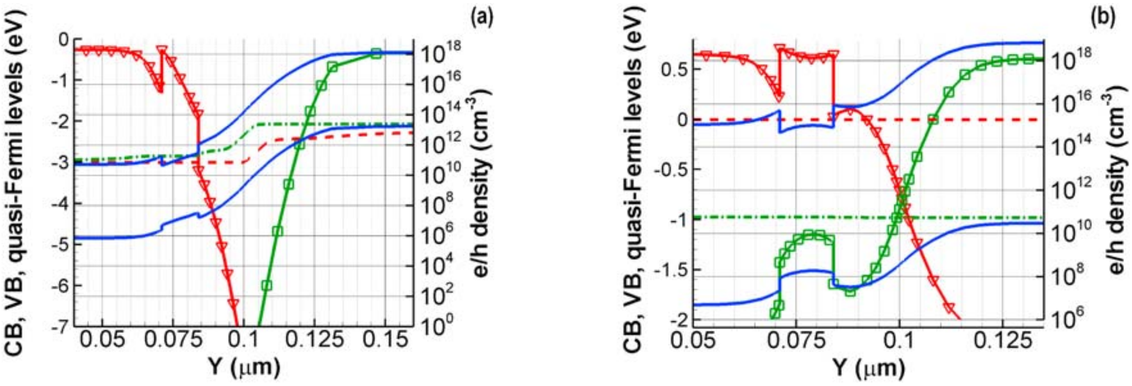

Fig. 2 (online colour at: www.pss-a.com) Cuts along AA′ (a) and CC′ (b) show conduction band and valence band (solid lines), QFLs (dash for electrons and dash-dot for holes), electron density (triangles) and hole density (squares) for reverse-biased (a) and forward-biased (b) regions of the device, respectively.

hole (e−h) density in the QW region grows with the applied bias and the radiative recombination rate and emitted light intensity also grows, as can be seen from Fig. 3. As is seen from Fig. 2b there is quite a large electron density in the QW, but the density of holes in the QW region at 3 V bias is still very low. As the applied voltage increases the density of holes in the QW grows rapidly and achieves the value of 2×10^{16} cm^{-3} at 20 V. Further increase of the bias does not lead to a corresponding increase of the hole density due to realisation of a flat-band voltage condition. We found that the best option for increase of the e−h density in the QW is to locate the QW in the p-doped top region.

A dramatic increase in the radiative recombination rate with bias is shown in Fig. 4 for the case of the QW positioned in the p-channel which is obtained by swapping the doping species in the top and bottom channels in Fig. 1b. In this case the radiative emission under flat-band conditions is increased by more than an order of magnitude in comparison with the case when the QW is placed in the n-channel. The physical reason for such behaviour is that it is easier to transfer the electrons from the n-channel into the QW with the high-density holes already present there than vice-versa, due to the position of the QW in the p-channel. This is in turn due to higher mobility of the electrons in comparison with the holes. For a

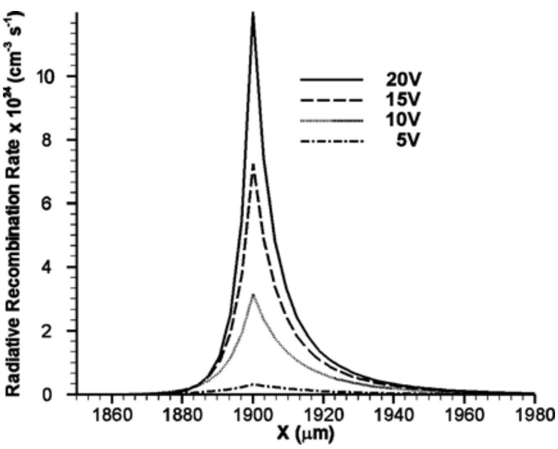

Fig. 3 Radiative recombination rate along the QW in n-channel of the THD emitter for various biases.

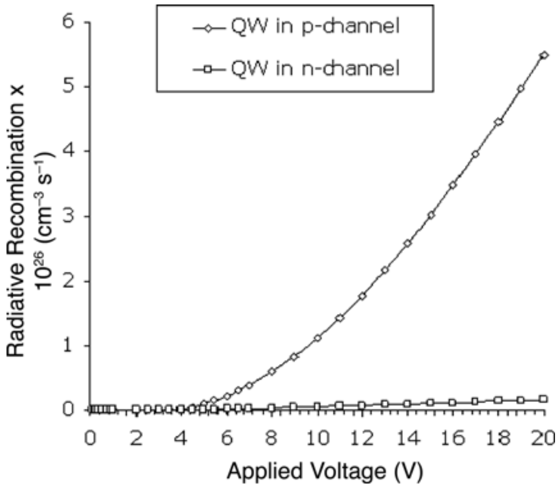

Fig. 4 Radiative recombination as a function of applied voltage for various position of the QW.

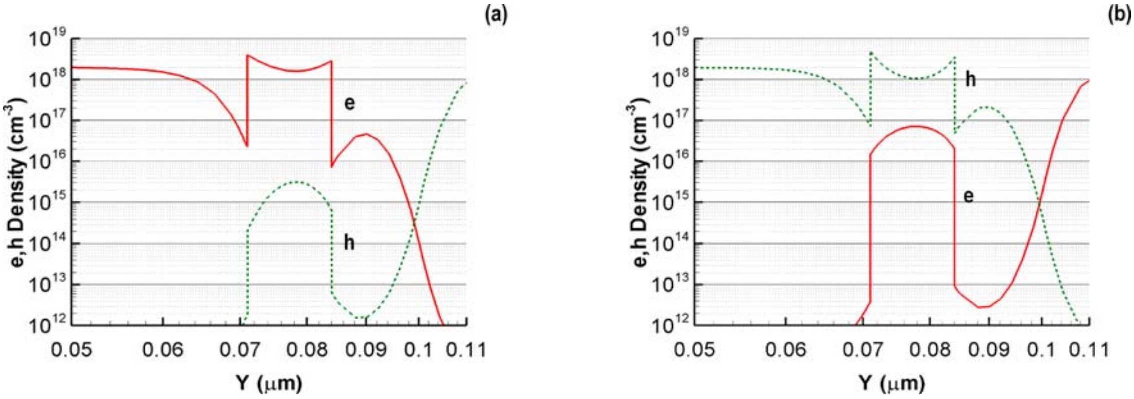

Fig. 5 (online colour at: www.pss-a.com) Peak e–h densities across QWs for THD with a) QW in n-channel and b) QW in p-channel at bias of 10 V.

given electric field strength the electron current is larger than the hole current and thus the rate of electron supply to the forward-biased region (where they are transferred into the QW) is also larger in comparison with the holes. This is shown in Fig. 5, which depicts the e–h densities corresponding to the peak of the radiative emission rate for different positions of the QW (QW in n-doped or in p-doped channel, respectively) at the same bias of 10 V. As seen from Fig. 5 for approximately the same density of the majority carriers which are already present in the QW (electrons in Fig. 5a, and holes in Fig. 5b), the injected density of the minority carriers is larger in case of the QW placed in the p-channel (Fig. 5b). This results in a larger magnitude of the product of the electron and hole densities and therefore higher radiative emission rate.

For optical power enhancement we further investigated various design options including asymmetry of the device in the *x*-direction, doping, and location of the QW. The light-voltage characteristics for various designs are shown in Fig. 6 where the QW was placed either in the n-channel (curves 1 to 5) or in the p-channel (curves 6 to 8). Since the radiative emission occurs in the forward-biased regions only, placing the top-channel more asymmetrically (the asymmetry increases for curves 1 to 8 in Fig. 6) we can alter the ratio of the forward and reverse biased regions to favour the former increasing the total emitted power. In order to evaluate the laser application potential of the THD emitters, we also calculated the optical gain in the QW region, which is shown in Fig. 7. As is seen from a comparison of Figs. 3 and 7, the spatial position (along the QW) of the peak of the radiative emission differs from that of the peak gain. This is explained by the different dependencies of radiative emission and gain on carrier

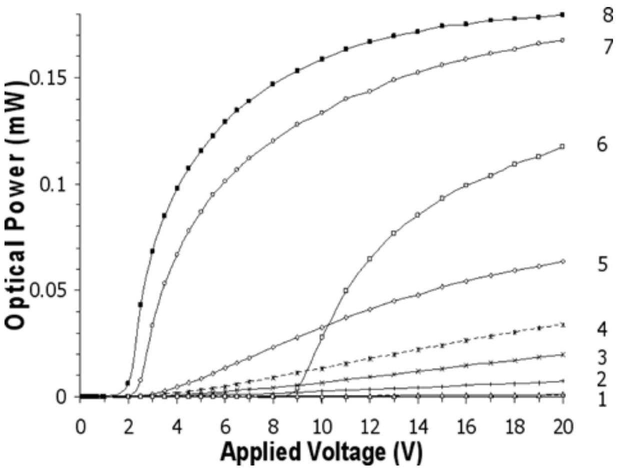

Fig. 6 Optical power against bias for various designs (1–8): 1 to 5 – QW in the n-channel; 6 to 8 – QW in the p-channel.

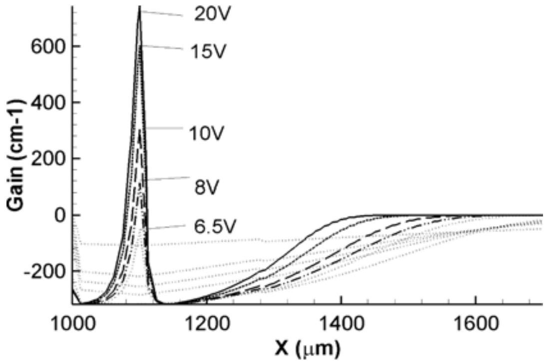

Fig. 7 Calculated material gain using the simulated carrier densities in the QW for various biases.

densities. It should be emphasised that in our device the electron and hole density distributions along the QW are highly inhomogeneous, contrary to the situation in conventional emitters.

4 Conclusions

We have presented the results of numerical modelling and simulation of a novel THD optical emitter with longitudinal e–h transport. We have shown that by altering the individual features (doping, THD asymmetry, location of the QW, etc.) the optical power can be increased by more than 400 times. The highest optical power generated by the single QW optimised device was around 0.18 mW.

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