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Electrical properties of InAs/InGaAs quantum-dot laser heterostructures: A threshold effect

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***Abstract*. We present differential current – voltage characteristics of InGaAs/GaAs laser structures with InAs quantum dots in a quantum well and without dots. In both cases, there is a drop in differential resistance at the lasing threshold, but in the case of the quantum-dot laser the drop is incomplete, without saturation of the voltage applied to the nonlinear part of the diode. The observed current voltage behaviour is interpreted qualitatively in terms of series-connected barriers (series barriers model).**

Keywords: *laser heterostructure, quantum dots, current – voltage characteristics, differential resistance.*

1. Introduction

Gain saturation in steady-state operation of a semiconductor laser leads to stabilisation of its quasi-Fermi levels and, hence, to saturation of the voltage across the injecting junction. Changes in the electrical characteristics of injection lasers at the lasing threshold were predicted by Basov et al. [1] and studied by Eliseev et al. [2]. Strictly speaking, it was not *a priori* clear what exactly should occur at the threshold because the homogeneity properties of the emission band of the semiconductor had not yet been studied. For this reason, it was not established how the Fermi levels would respond to the accelerated consumption of excess carriers in the lasing regime. It turned out that the dominant tendency was towards voltage saturation, which corresponds to spectrally homogeneous behaviour. Deviations from such behaviour, accompanied by mode hopping, and multimode lasing were attributed to spatial inhomogeneities [2]. Therefore, from the viewpoint of electrical characteristics the spontaneous and stimulated emission processes differ in that the latter leads to saturation of the bias applied to the injecting p – n junction.

If the voltage across a p – n junction, V, tends towards saturation above threshold, further increase in pump current, I, will cause no increase in V, which corresponds to zero differential resistance of the p – n junction. This was demonstrated in [2] and was confirmed in later studies [3 – 6]. The differential threshold effect is well illustrated by the plot Fig. 1, which shows the differential resistance of an InGaAs/GaAs quantum-well laser diode. If the nonlinear component of the diode resistance obeys the well-known formula $V(I) = (nkT/e)\ln(I/I_s)$, where n is the nonideality factor and I_s is the saturation current, the differential resistance is a linear function of $x = 1/I$:

$$\frac{dU}{dI} = R_s + \frac{nkT}{e}x. \qquad (1)$$

Therefore, if subthreshold data are represented by a straight line on such a plot, one can easily assess the linear and nonlinear components of the diode resistance. In the case under consideration, $n = 1.43$. In the Shockley model (low injection level, nondegenerate system) $n = 1$ [7], and in the Hall model $n = 2$ [8].

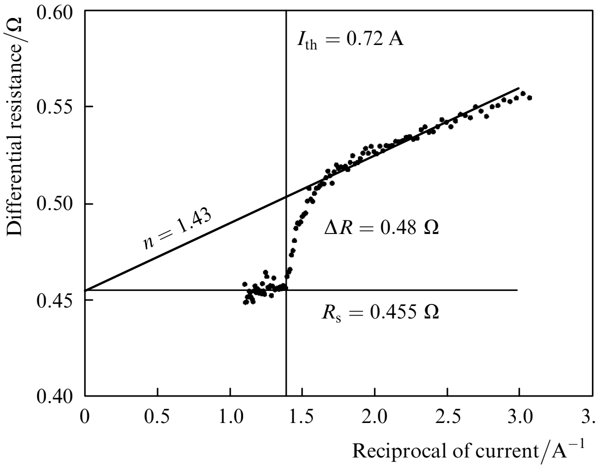

Figure 1. Differential resistance versus reciprocal of diode current for a strained-layer InGaAs/GaAs/AlGaAs quantum-well laser structure. The inclined line represents the subthreshold behaviour of the laser (spontaneous emission) with a nonideality factor $n = 1.43$, and the horizontal line represents the residual resistance of the diode, R_s. Above the threshold current, $I_{th} = 0.72$ A, the data points fall on the horizontal, which corresponds to zero differential resistance of the p – n junction.

Note that, in practice, one usually measures not the voltage across the p – n junction, V, but the diode voltage, U, which includes the voltage drop across the passive layers and contacts. As shown earlier [9, 10], if injection leads to nonlinear conductivity of these layers, the threshold behaviour of the diode may differ drastically from the behaviour

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of the p – n junction, e.g. the differential effect may have the opposite sign. There are also other factors that hinder direct observation of the threshold saturation effect, in particular, carrier leakage and the shunting effect of nonlasing regions.

In this paper, we examine the threshold and above-threshold behaviour of InAs/InGaAs dots-in-a-well (DWELL) lasers [11, 12]. This laser structure differs from that represented in Fig. 1 in that its active region contains quantum dots capable of rapidly capturing excess carriers from the quantum well. Recombination in the quantum dots increases the lasing wavelength (from 980 to ~ 1250 nm).

The question is whether the injecting p – n junction (its forward bias) is sensitive to the dominant type of recombination (spontaneous or stimulated) in the quantum dots. Recall that carriers are injected from the AlGaAs emitter regions to the GaAs waveguiding layers and are then captured by the InGaAs quantum well and finally by the InAs quantum dots. Lasing begins after the carriers lose a significant part of their energy as a result of the three-step capture process. In particular, at the lasing threshold the voltage across the p – n junction is 1.565 V, and hence the energy needed to produce an excess electron hole pair is 1.565 eV. The emitted photon energy is ~ 1.0 eV. Therefore, about 565 meV, i.e. more than one-third of the pump energy, goes into the thermalisation of captured carriers. By analogy with a waterfall (the analogy often used in interpreting the injection process in heterojunctions), no carrier counterflow would be expected. Thus, it is not clear beforehand how and to what extent the voltage across the upper electron reservoir will depend on the quasi-Fermi levels in the lower one. The experimental results presented here demonstrate that the diode voltage is sensitive to threshold saturation, and the subject of discussion is incomplete bias saturation above threshold.

2. Experimental and results

We used DWELL diodes with InAs quantum dots [11]. The structures were grown by molecular beam epitaxy on GaAs substrates. The salient feature of such lasers is that InAs quantum dots are inserted in an InGaAs quantum well, which is the basic component of the laser structure, similar to the structure of InGaAs strained layer lasers (GaAs waveguiding layers, InGaAs emitter layers and intermediate graded layers intended to reduce the electrical resistance of the structure). The quantum dots had the shape of pyramids or truncated pyramids (base diameter, 15 – 20 nm; height, 7 – 10 nm). The quantum well thickness was 9.6 – 10 nm, and the in-plane quantum dot density was $\sim 3 \times 10^{10}$ cm^{-2}.

Because of the low modal optical gain, corresponding in such structures to the major emission band of the quantum dots, the cavity of the device was made rather long (3.474 mm), in the form of a spatially single-mode ridge stripe 2 μm in width. Current voltage measurements were made at room temperature and currents from 5 to 100 mA, i.e. up to almost five times threshold current under cw conditions (Fig. 2). The emission wavelength was ~ 1250 nm. The lasing spectrum was multimode, 2 – 5 nm in width. The diode voltage varied from 1.565 V at the threshold current to 1.590 V at the highest current.

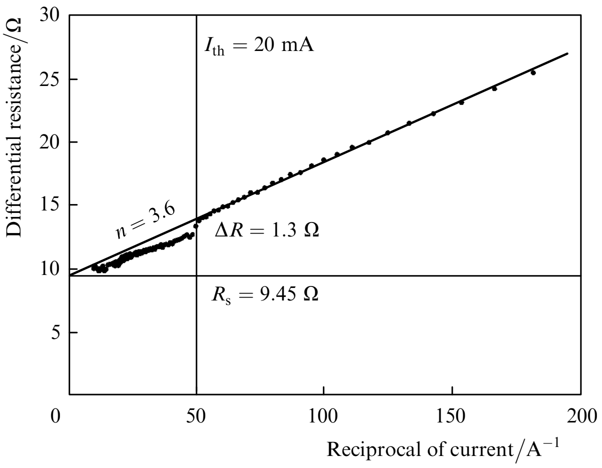

Figure 2. Differential resistance versus reciprocal of diode current for a DWELL laser structure (InAs/InGaAs/GaAs/AlGaAs with InAs quantum dots). The threshold current is 20 mA, and the nonideality factor is 3.6 below threshold and 2.6 above threshold.

3. Discussion

Figure 1 presents an example where the differential resistance of the p – n junction in a 980-nm long-cavity InGaAs/GaAs quantum-well laser drops to nearly zero at the threshold current. (Similar behaviour of such lasers was reported earlier [13].) At the threshold current (0.72 A), the differential resistance data show a transition from an inclined line with $n = 1.43$ to a horizontal line, corresponding to the residual resistance of the passive regions and contacts: $R_s = 0.455$ Ω. This is supported by the fact that the two linear portions of the curve converge in the limit of infinite current as a result of the assumed monotonic reduction in the differential resistance of the p – n junction. Since the nonlinear differential resistance almost vanishes, it seems likely that the voltage across the p – n junction is governed by the quasi-Fermi level separation in the InGaAs quantum well.

In Fig. 2, the drop in differential resistance at the threshold current is obviously incomplete: at a current of 20 mA, the resistance decreases by $\Delta R = 1.3$ Ω instead of the expected 4.5 Ω. The residual resistance of the diode is 9.45 Ω as determined by extrapolating the subthreshold linear portion to infinite current. Thus, the differential resistance of the junction decreases at the threshold current by about 29 %. Above threshold, the plot has a nearly constant slope, with a nonideality factor of ~ 2.6.

Our experiments indicate that the differential resistance of the diode drops at the lasing threshold, which implies that the diode voltage is sensitive to the recombination regime in the quantum dots in spite of the three-step carrier capture process. To understand the origin of this sensitivity, a multilayer laser heterostructure can be thought of as a series combination of electrical barriers, with bias saturation at the barrier responsible for injection into active states (into quantum dots in our case). The other barriers may be insensitive to the lasing regime (e.g. they may fit the analogy with a waterfall). It may be that partial barriers correspond to the interfaces between heterostructure layers. Since partial biases add up together, the total bias is sensitive to the lasing threshold. It follows from experimental data that lasing-insensitive barriers lead to incomplete voltage saturation. As to the saturable barrier, there seems to be a dynamic balance between antiparallel carrier flows, which leads to voltage saturation. Such junctions obey the principle of communicating vessels, rather than fitting the analogy with a waterfall.

The series barriers model is considered in the Appendix. In this model, the total nonideality factor of a diode is the sum of the nonideality factors of partial barriers if these are connected in series. In the case under consideration, the total factor is 3.6 and the above-threshold slope is $n_{\text{res}} = 2.6$. Therefore, the nonideality factor of the sensitive barrier is unity (Shockley p–n junction). Such 'ideality' is typical of nondegenerate p–n junctions and corresponds to small deviations from equilibrium. The junction between the waveguiding (undoped) layers and the InGaAs quantum well (also undoped) fulfils these conditions given that achieving dynamic population degeneracy in quantum dots does not require population degeneracy in the quantum well. Moreover, because the capture time of quantum dots is very short, large deviations from equilibrium cannot be produced in the quantum well. The behaviour of quantum dots is similar to that of deep impurity-related recombination centres. As shown earlier [12], their average optical cross section is $\sim 7.3 \times 10^{-15}$ cm^2. Therefore, in the case of complete population inversion in quantum dots, these ensure a gain of ~ 200 cm^{-1}.

Strictly speaking, incomplete voltage saturation may also be due to injection-induced conductivity effects [8]. In our case, such effects may be of some importance because induced conductivity is possible, to varying degrees, in many types of laser diodes. According to our estimates, however, its contribution is insignificant because it saturates below threshold. Generally, any electrical nonlinearities (barriers, injection-induced conductivity layers) connected in series with the laser p–n junction may obscure the saturation effect, in particular, leading to incomplete diode voltage saturation.

4. Conclusions

The differential resistance of InAs-based quantum-dot laser structures is shown to drop at their lasing threshold. The drop is, however, incomplete (not to zero), and the above-threshold current–voltage curve of the laser structures shows further decrease in differential resistance with decreasing nonideality factor. The behaviour of the lasers studied can be understood in terms of the series barriers model.

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Appendix

Series barriers model

Consider a series of electrical barriers each of which can be represented by a current voltage characteristic of the form $V_i = V_{0i} \ln (I/I_{0i})$, where the subscript i refers to partial parameters. In the case of a series combination, the partial voltages add up together to give the total diode voltage

$$U(I) = IR_{\text{s}} + V_0 \ln \frac{I}{I_0}, \tag{A1}$$

where $V_0 = \sum_i V_{0i}$ and $I_0 = \Pi_i(I_{0i}^{V_{0i}/V_0})$. Therefore, this simple formula remains applicable by virtue of the new relations between cumulative and partial parameters of current voltage curves. It can be seen that V_{0i} are additive quantities independent of the voltage drop across a given partial barrier. The total nonideality factor can be defined as $n_0 = V_0/kT$, that is, as the sum of the nonideality factors of the partial barriers:

$$n_0 = \sum_i n_i. \tag{A2}$$

This accounts for the anomalously large nonideality factors of some diodes. If one of the partial barriers, which is responsible for pumping, saturates, its contribution to nonideality, n^*, should be subtracted from the total nonideality factor. The residual nonideality of the current voltage characteristic above threshold is then

$$n_{\text{res}} = n_0 - n^*. \tag{A3}$$

It is of interest to note that, in a study of the nonideality effect on incomplete voltage saturation in GaAs/AlGaAs double heterostructure lasers [14], the following empirical relation was derived:

$$V_{\text{res}} = \frac{kT}{e}(n-1) \tag{A4}$$

where V_{res} is the residual diode voltage above the lasing threshold and n is the subthreshold nonideality factor. From (A3) and (A4), we obtain $n^* = 1$. This suggests that the current voltage behaviour of the barrier responsible for bias saturation follows the Shockley model [7].

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