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Numerical Simulation of Auger-Induced Hot Electron Transport in InGaAsP/InP Double Heterojunction Laser Diodes: Hydrodynamics versus Drift and Diffusion

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Abstract

A strategy for the numerical simulation of Auger-induced hot electron transport related to the electron leakage problem encountered in the design and analysis of InGaAsP/InP laser diodes is presented. The theoretical structure used in conventional device simulation is extended to include the otherwise neglected interactions between the Auger hot electrons and the low-energy carriers in the device. The transport behavior of the Auger hot electrons is examined from both the hydrodynamic and the drift-diffusion perspectives.

1. Introduction

Electron leakage in InGaAsP/InP laser diodes originates from the overflow of the Auger-induced energetic electrons from the active region over the heterobarriers into the adjacent cladding layers. This causes significant loss of electrons that may otherwise undergo radiative recombination for light emission. This loss is reflected in the increase in the threshold current density [1] - [3]. The Auger hot electron concentration is typically two to three orders of magnitude smaller than that of the low-energy electrons in the active region [4]. Therefore, without detailed knowledge of the high-energy tail of the electron distribution function, the transport characteristics of these energetic electrons cannot be modeled using an average description of all the electrons in the device as a single system. As is well known, this average description forms the basis of conventional device simulation, in which the physical origins of the charged carriers are often ignored because of the global averaging process involved in the derivation of the semiconductor equations [5]. This renders existing device simulation programs not directly applicable to the analysis of the electron leakage problem in double heterojunction laser diodes.

To alleviate such difficulties, we present an expedient approach by extending the structure used in conventional device simulation to capture the otherwise neglected interactions between the Auger hot electrons and the low-energy carriers in the device.

The extension is achieved by decomposing the conventional electron current continuity equation into two components, with one for the Auger hot electrons, and the other for the low-energy electrons. This allows one to track down explicitly the transport behavior of the Auger hot electrons within the conventional device simulation environment. Coupling these two current continuity equations is an appropriately derived set of carrier statistics terms that account for the Auger, the Shockley-Read-Hall, and the spontaneous recombination processes. We present the simulation results for a one dimensional N-p-P InGaAsP/InP laser diode with composition corresponding to 1.3 μm emission wavelength. Hydrodynamic equations formulated for heterostructures [6] are used to model the dynamics of the Auger hot electrons, whereas drift-diffusion transport is assumed for the low-energy electrons and holes. Fermi-Dirac statistics is used in the simulation.

2. Problem Formulation

In the studies of the electron leakage problem in double heterostructure laser diodes, the electron system should be considered as consisting of an low energy electron gas interacting with a population of Auger-induced energetic electrons. A macroscopic description of the conservation of these two categories of electrons leads to the following continuity equations for the Auger hot electron current density $\vec{J_{n'}}$ and the cool electron current density $\vec{J_{n_c}}$, respectively,

$$-\frac{1}{q}\nabla\cdot\vec{J_{n'}} = G_{aug}\big|_{n'} - R_{spon}\big|_{n'} - R_{srh}\big|_{n'} - \frac{n'}{\tau} \tag{1}$$

$$-\frac{1}{q}\nabla\cdot\vec{J_{n_c}} = -R_{aug}\big|_{n_c} - R_{spon}\big|_{n_c} - R_{srh}\big|_{n_c} + \frac{n'}{\tau} \tag{2}$$

where the energy relaxation time τ appearing in (1) models the relaxation process of the Auger hot electrons due to intraband scatterings. The meaning of the generation and recombination terms on the right of (1) and (2) can be seen from their self-explanatory subscripts. These generation-recombination terms are given by

$$G_{aug}\big|_{n'} = C_n n(pn - n_i^2). \tag{3}$$

$$R_{aug}\big|_{n_c} = (2C_n n + C_p p)(pn - n_i^2). \tag{4}$$

$$R_{spon}\big|_{n'} = Bn'p \tag{5}$$

$$R_{spon}\big|_{n_c} = B[n_c p - n_i^2] \tag{6}$$

$$R_{srh}\big|_{n'} = \frac{\tau_p n_1 n'/\tau_n + pn'}{\tau_n(p+p_1) + \tau_p(n+n_1)} \tag{7}$$

$$R_{srh}\big|_{n_c} = \frac{-\tau_p n_1 n'/\tau_n + pn_c - p_1 n_1}{\tau_n(p+p_1) + \tau_p(n+n_1)} \tag{8}$$

where the electron concentration n is given by the sum of the Auger hot electron concentration n' and the cool electron concentration n_c. The parameters appearing in the above generation-recombination terms have their usual physical meanings. Note that the factor of two in (4) accounts for the loss of two low energy electrons in each CHCC events in order to create one Auger hot electron.

In this work, the following conservation equation for the Auger hot electron energy $W_{n'}$ is used

$$\nabla\cdot\vec{S}_{n'} - \nabla E_c\cdot\frac{\vec{J}_{n'}}{q} - G_{aug}\big|_{n'}E_g = -n\frac{W_{n'}-W^0_{n'}}{\tau} - \left[\frac{n'}{\tau} + R_{spon}\big|_{n'} + R_{srh}\big|_{n'}\right]W_{n'}. \quad (9)$$

A recombination energy equal to the energy gap E_g of the material is assumed. The hot electron energy flux $\vec{S}_{n'}$ and $\vec{J}_{n'}$ are treated using the formulation given by Azoff [6]. These equations are solved together with the Poisson and the hole current continuity equations for self-consistent solutions.

3. Simulation Results and Discussion

Fig.1 shows a schematic diagram of the device considered in this work. Fig.2 shows the energy distribution of the Auger hot electrons in the device. The injection current density is 7.4 kA/cm^2. The energy gradient throughout the device causes enhanced

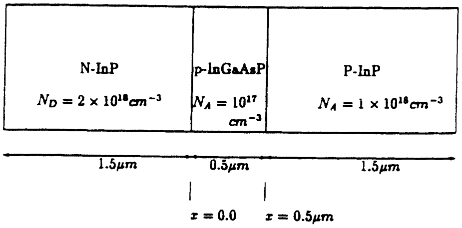

Figure 1: Schematic diagram of the InGaAsP/InP laser diode

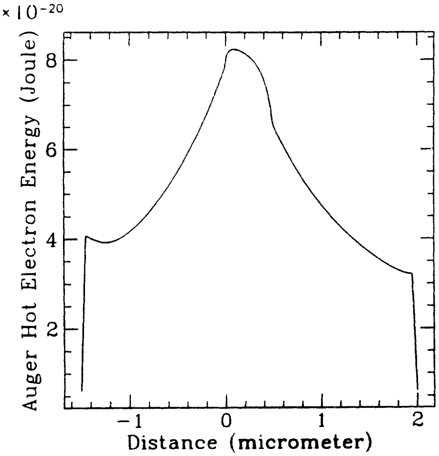

Figure 2: Auger hot electron energy distribution

diffusion of the hot electrons into the P-InP cladding layers. This is illustrated in Fig.3, where profiles of the Auger hot electron concentration obtained from the hydrodynamic and the drift-diffusion equations are compared. The drift-diffusion result shows a highly asymmetrical distribution of the Auger hot electrons. The Auger hot electron concentration in the N-InP layer is much higher than that in the P-InP region. This is consistent with the fact that, unlike the p-P heterojunction, the built-in field across the N-p heterointerface favours the overflow of hot electrons into the N-InP layer. However, with the effects of energy transport included, the hydrodynamic result shows a high degree of symmetry in the distribution of the hot electrons. This indicates the dominant role played by energy transport in the simulation of electron leakage in double heterostructures. This point is best illustrated by a direct comparison of the Auger hot electron current density distribution obtained from the hydrodynamic and the drift-diffusion equations, as depicted in Fig.4. It can be seen that the Auger hot electron current density peaks at the two heterointerfaces, indicating Auger hot electron leakage across both the p-P and the N-p heterobarriers. The drift-diffusion result, however, fails to capture the leakage process across the p-P heterointerface.

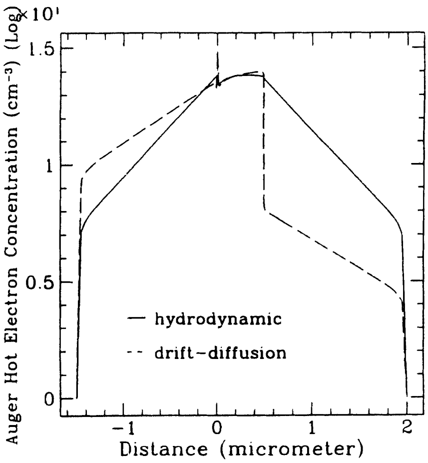

Figure 3: Auger hot electron concentration

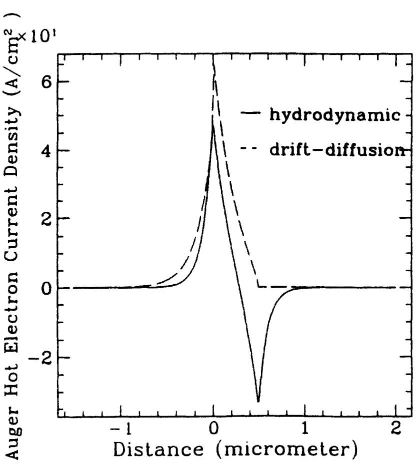

Figure 4: Auger hot electron current density

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