Edited by H. Ryssel, P. Pichler - September 1995

Modeling of a Hot Electron Injection Laser

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Abstract

Device concept and model of a vertically integrated transistor-laser structure for a dual gain-switching involving carrier heating are reported. Capability of a proposed three-terminal device to generate high-intensity picosecond pulses is studied using numerical simulation.

1. Introduction

Dynamic carrier heating effects in semiconductor laser diodes (LD's) attract much attention because of their potential use for a high-speed modulation [1-3]. Particularly, variation of the carrier effective temperature, properly combined with variation of the carrier concentration, has been shown as a recipe for a drastic improving the high-speed performance of gain-switched lasers [4-6]. To implement this modulation technique, an acceptable mechanism to control the carrier effective temperature should be, however, found. The possible solution is associated with injection of hot, variable energy, electrons as means to pump an LD, that can be achieved with a recently proposed three-terminal device combining the transistor and the laser features [6]. In this paper, the model of such a device, labeled as a hot electron injection laser (HEIL), is reported and the device capability of generation of good-shaped gain-switched pulses is analyzed.

2. Device concept

The schematic cross-section of a HEIL is shown in Fig. 1. The device represents a vertically integrated structure, in which an LD is inserted in the collector area of a hot electron transistor (HET). It is assumed, that electrons, injected from n^+- emitter, traverse the base with a transport ratio close to unity and then are accelerated into the high electric field of a collector barrier. The latter thus serves as a hot electron launcher, positioned between the base of a HET and the active region (AR) of an LD. The laser input is associated with both the carrier injection rate J, and the energy injection rate, Q, which two are connected by $Q = \varepsilon_J \times Q$, where ε_J is the energy yield per one injected electron-hole pair [4]. To vary the electron contribution to this parameter, ε_C, and inject therefore carriers at controlled energy is, after all, the idea of a HEIL. On time-scales above the time of transitional processes in electric circuit, this is implemented by two drive voltages, V_1 and V_2, applied as shown in Fig. 1. Hot electrons, injected by emitter-base biasing and then heated in electric field of a launcher, lose their energy mainly due to intercarrier scattering into an AR and so within a short thermalization time they increase the tempe-

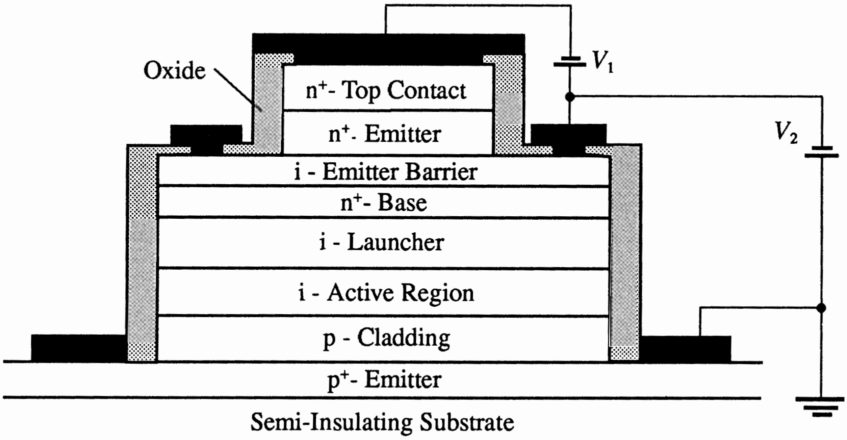

Fig. 1. Schematic structure of a hot electron injection laser.

rature of a thermalized sea along with increase of its concentration. As far as these two parameters govern the material gain, by imposing the data in signal on drive voltages one gets the possibility of a dual - concentration and temperature - gain-switching.

The device performance depends, however, on the range of change in ε_C, which is determined by the mechanism of electron transport over the launcher. If electrons traverse this region with no scattering, one benefits from injection at narrow energy distribution, that can be achieved by employing the resonant-tunneling structure as an emitter barrier [6]. In this case, hot electrons enter an AR at well-defined and variable energy, which is just ε_C. For a high scattering intensity, ε_C is determined by the level of Joule heating into the launcher and does not depend on the initial energy distribution. In that case no need for resonant-tunneling injection and a single emitter barrier of any type can be employed.

3. Model

As far as lasing is directly controlled by the carrier and the energy injection rates, not by drive voltages, the task of a HEIL modeling is divided in two following steps: 1) to find an optical output of an LD in response to $J(t)$ and $Q(t)$ as the given functions of time, and 2) to connect $J(t)$ and $Q(t)$, on the one hand, and electrical input of a device, on another.

At the first step, the earlier reported model, describing an LD as a nonequilibrium system consisting of the electrically injected carriers, the LO-phonons and the guided photons, interacting with each other [1], is employed. Homogeneity and the thermalization of the electron-hole plasma inside an AR are assumed on all actual time-scales, and the model is therefore reduced to a set of the rate equations, written for plasma concentration and effective temperature, LO-phonon occupation number and effective photon population associated with a lasing mode. By making use from the evident form of distribution functions of thermalized carriers, the interaction processes are described microscopically, the details of these calculations have been recently published elsewhere [3].

At the second step, it is assumed, that carrier injection rate, J, is a known function of emitter-base and base-collector bias voltages of a HET, V_1 and V_2 - $\Delta\Phi_{cv}$, respectively, where $\Delta\Phi_{cv}$ is the Fermi quasilevels splitting inside an AR. Thus, the problem reduces to find the energy coupled to one injected electron, ε_C. In a case that inelastic scattering into a launcher can be neglected, resonant-tunneling injection at narrow energy distribution is assumed. Then, ε_C, derived from the energy conservation condition, is

$$\varepsilon_C = \varepsilon_B(V_1) + eV_2 - \Delta\Phi_{cv} - \mu_B + \mu_C,$$

where $\varepsilon_B(V_1)$ is V_1 - dependent resonant-tunneling level, referred to the conduction band edge in a base, μ_B and μ_C are the chemical potentials of electrons in a base and an AR, respectively. In the opposite ultimate case, when phonon and intercarrier scattering are just the processes which govern the transport over a launcher, the single-temperature approximation is employed to describe the energy distribution of hot electrons in a high electric field. The Γ-L nonparabolic conduction band model is assumed, the electrons in Γ and four equivalent L valleys being described by the same effective temperature, T. The latter is determined from the balance condition, equalizing the Joule power and the energy relaxation rate due to inelastic phonon scattering, that is accounted under the homogeneous drift approximation. The relevant intra- and intervalley scattering processes are described microscopically, in a way, similar to that used in the conventional Monte Carlo simulations [7]. At the same time, the evident - Maxwellian - shape of the energy distribution is essentially used to obtain the macroscopic transport characteristics of hot electrons. The energy yield, ε_C, is then given by

$$\varepsilon_C = \frac{(1+3\alpha_\Gamma T)\,(\Delta_C + 2T) + R_{L\Gamma}(T)\,(1+3\alpha_L T)\,(\Delta_C + \Delta_{L\Gamma} + 2T)}{1 + 2\alpha_\Gamma T + R_{L\Gamma}(T)\,(1+2\alpha_L T)},$$

where Δ_C is the conduction band offset at the AR' edge of a launcher, $\Delta_{L\Gamma}$ is the energy gap between L- and Γ-valleys into the launcher, $R_{L\Gamma}(T) = 4(m_L/m_\Gamma)\times\exp(-\Delta_{L\Gamma}/T)$, m_i and α_i are the effective mass and the parameter of nonparabolicity in i-th valley, i = Γ, L. When deriving this equation, the transitions in real space between the equivalent valleys only are taken into account [8], and scattering by thermalized carriers is considered as a dominant energy relaxation channel for hot electrons entering an AR.

4. Modeling results

The subject of the present study is a HEIL using In(AlGa)As/InGaAsP/InP material system, operating in a wavelength 1.55 μm at room temperature. Only lasers with a bulk AR are assumed, because of the carrier bottleneck effect in a typical separate-confinement quantum-well laser makes the intended control of the enegry injection rate less efficient. A modeling example of the picosecond pulse generation from a HEIL is shown in Fig. 2. Here, the carrier injection rate remains constant (at a level $J = 3.10^{27}$ cm^{-3}s^{-1}) and the gain-switched optical pulse proceeds from modulation of only the energy injection rate, that is achieved by varying of ε_C. The stationary value is chosen high enough to suppress the generation by carrier heating coupled to injection [3, 5] and so the steady state of an LD is below the threshold. Then, switch *on* is caused by carrier cooling and switch *of* - by reverse carrier heating, produced by lowering and raising of ε_C, respectively. Note, that intensity of so switched pulse depends on the depth of the deep in a carrier temperature (which is less than 2 meV for a given numerical example) and hence it can be improved by enlarging the range of change in ε_C. To evaluate the device potential in this line, the energy yield per one injected electron, ε_C, has been computed in dependence on

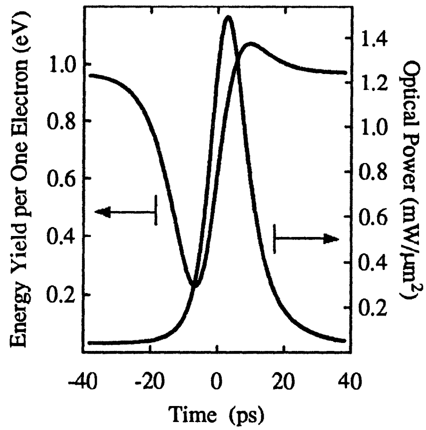

Fig. 2. Generation of picosecond optical pulses from HEIL switched by varying of energy ε_C.

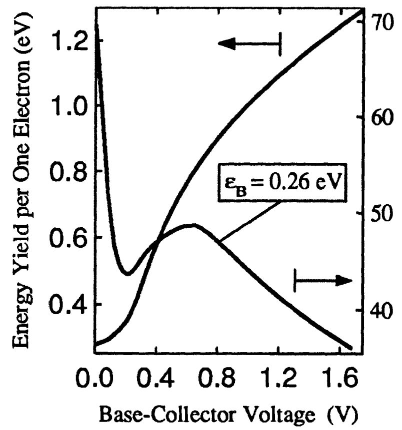

Fig. 3. Energy yield per one injected electron and effective free path as functions of bias $V_2 - \Delta\Phi_{cv}$.

a base-collector bias voltage, $V_2 - \Delta\Phi_{cv}$, for two above-mentioned ultimate cases of collisionless resonant-tunneling injection and homogeneous drift over the launcher. Transition from the first to the second occures when an effective free path, λ_{eff}, defined as

$$\frac{1}{\lambda_{eff}} = \frac{1}{\varepsilon_2 - \varepsilon_1}\int_{\varepsilon_1}^{\varepsilon_2} \frac{1}{\lambda(\varepsilon)} d\varepsilon$$

where ε_1 and ε_2 are the initial and the final energies of a resonant-tunneling electron into a launcher and $\lambda(\varepsilon)$ is the enegry-dependent free path of a probe electron there, is getting less than the width of a collector barrier. Calculated value of λ_{eff} is plotted in Fig. 3 as a function of $V_2 - \Delta\Phi_{cv}$ for InP launcher. It is seen, that the probability of a collisionless transport over the collector barrier drops drastically with raising of a base-collector bias voltage in a range, needed for a high-intensity pulse generation by the above-described scheme. The drift mechanism of transport over the launcher is therefore more probable for any reasonable width of it. The associated energy yield per one injected electron is also given in Fig. 3 in dependence on $V_2 - \Delta\Phi_{cv}$ for InP launcher. By comparing these data with ones shown in Fig. 2, it is concluded that variable Joule heating in a launcher is just a mechanism insuring generation of high-intensity picosecond gain-switched pulses.

References

[1] V. I. Tolstikhin, *Techn. Phys. Lett.*, **18**, 630 (1992).
[2] S. V. Polyakov and V. I. Tolstikhin, *Techn. Phys. Lett.*, **19**, 110 (1993).
[3] V. I. Tolstikhin and M. Willander, *IEEE J. Quantum Electron.*, **QE-31**, 814 (1995).
[4] V. Gorfinkel and S. Luryi, *Appl. Phys. Lett.*, **62**, 2923 (1993).
[5] V. I. Tolstikhin and M. Willander, *J. Appl. Phys.*, **77**, 488 (1995).
[6] V. I. Tolstikhin, A. N. Mamaev, and M. Willander, *J. Appl. Phys.*, (to be published).
[7] W. Fawcett, A. Boardman, and S. Swain, *J. Phys. Chem. Solids*, **31**, 1963 (1970).
[8] I. C. Kizilyalli and K. Hess, *J. Appl. Phys.*, **65**, 2005 (1989).