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Three-terminal laser structure for high-speed modulation using dynamic carrier heating

Valery I. Tolstikhin[a]
Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden

Marco Mastrapasqua[b]
Eindhoven University of Technology, Faculty of Electrical Engineering and COBRA Institute,
P. O. Box 513, 5600 MB Eindhoven, The Netherlands

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A three-terminal laser structure is proposed as a means to achieve laser modulation using dynamic carrier heating. The injection of hot electrons, with energy tuned by variable joule heating over a high electric field region, is used to govern the carrier temperature in the active layer of a laser, while a separate heterojunction controls the injection rate. Simulations show the possibility of generating good-shaped picosecond optical pulses by modulating the voltage that controls the heating electric field. © *1995 American Institute of Physics.*

Carrier heating induced dynamics of semiconductor laser diodes (LDs) has gained significant interest due to its potential for a high-speed modulation. The idea is to employ fast relaxing changes in carrier effective temperature, T_e, instead of,[1] or in complement to[2,3] relatively slow variations of carrier concentration, N_e. The ultrafast gain dynamics caused by carrier heating and cooling has been observed in pump-probe experiments,[4,5] and the T_e switching has been shown, by numerical modeling,[6] to be able to produce good-shaped, low-chirp picosecond optical pulses. Different practical methods to realize a controllable modulation of T_e inside an active region (AR) of a lasing device have been proposed.[7,8] Recently, a three-terminal device structure, combining a resonant-tunneling transistor and an injection laser, has been suggested for this purpose.[6] The integration of a transistor with an LD is intended to provide a way to independently control the carrier injection rate, *J*, and the energy, yielded in the AR plasma as a result of injection of one electron-hole pair, ϵ_J. Carrier temperature inside the AR is directly affected by this parameter and can, therefore, be tuned by imposing a signal on the drive voltage(s) responsible for the change of ϵ_J. A rough estimate of the required change in ϵ_J gives $\Delta\epsilon_J \cong (\tau_N/\tau_T)\Delta T_e$ (hereafter T_e is measured in energy units), where $\Delta\epsilon_J$ and ΔT_e are the variations of ϵ_J and T_e, respectively, τ_N and τ_T are the relaxation times for concentration and effective temperature of a dense thermalized electron-hole plasma.[9] Usually $\tau_N \cong 1$ ns and $\tau_T \cong 1$ ps,[9,10], i.e., to get a reasonable variation of T_e around 1 meV,[3] a variation of ϵ_J as large as 1 eV is necessary. Assuming the resonant-tunneling injection, as proposed in Ref. 6, as means to pump an LD, this meets certain objections.[11] In this letter, we propose and theoretically investigate a novel three-terminal structure, which is believed able to achieve the required ϵ_J modulation, and, at the same time, to reduce device complexities.

The schematic cross section and the energy band diagram of the proposed device, labeled as a bipolar injection hot electron laser (BIHEL), is shown in Figs. 1(a) and 1(b), respectively. The structure is a result of the integration of a standard InGaAsP/InP double heterostructure LD[12] with a bulk[13] AR within the collector region of an InP/InGaAsP single heterojunction bipolar transistor.[14,15] The collector mesa of the modified transistor should be made sufficiently narrow to have lateral optical index guiding and assure single mode operation. In operative conditions, two drive voltages,

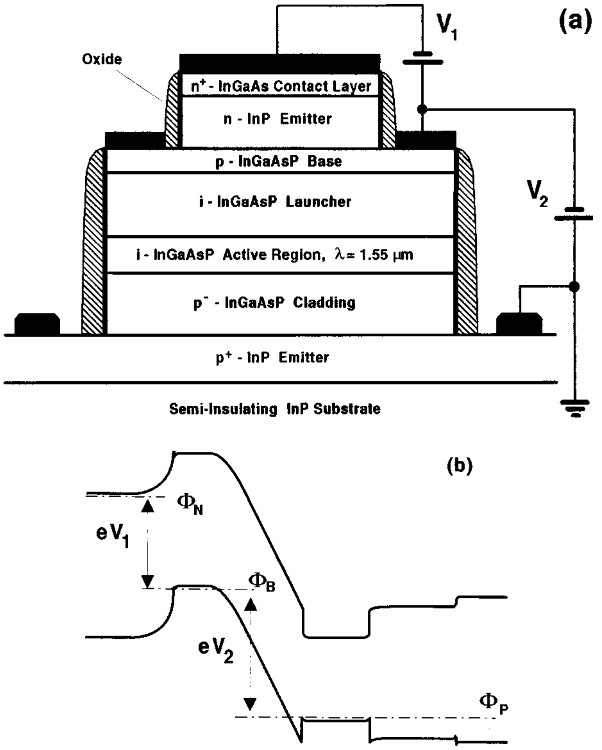

FIG. 1. Schematic (a) cross section and (b) energy band diagram of the proposed three-terminal laser structure, using InGaAsP, lattice matched to InP, material system. Both *i* launcher and *p* claddings are eventually graded layers, with band gap narrowing towards the active region. Φ_N, Φ_P, and Φ_B are the Fermi levels in *N*, *P* emitters, and base, respectively.

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[a] On leave from the Institute of Radio Engineering and Electronics of the Russian Academy of Sciences, 11 Mokhovaya, 103907 Moscow, Russia.

[b] Electronic mail: marco@cobra.tue.nl

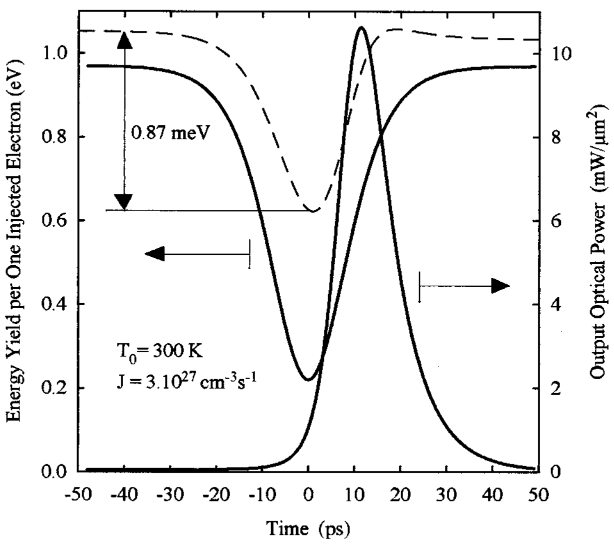

FIG. 2. Generation of picosecond gain-switched pulse by varying the energy yield associated with injection of one electron. Dashed line gives the related time scan of change in carrier effective temperature, in arbitrary units. The carrier injection rate, *J*, is accounted per unit volume of active region.

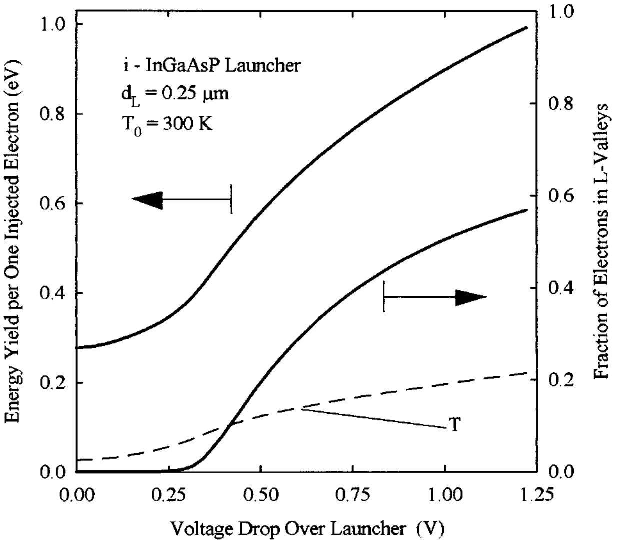

FIG. 3. Energy yield in the AR plasma, as a result of injection of a single electron, function of the voltage drop over the launcher. Dashed line shows the effective temperature of electrons, heated by joule mechanism, at the end of the launcher.

V_1 and V_2, as shown in Fig. 1(a), are applied between the base and top N^+ and bottom P^+ emitters, respectively. Electrons are injected through the emitter-base junction, travel across the base, and after acceleration by the electric field over the launcher, they enter the AR. The bias voltage V_2 is divided between the AR and the launcher in a proportion, that ensures the quasineutrality of the thermalized electron-hole plasma inside the AR. When the quasineutrality condition is met, the voltage drop over the AR is equal to the electron to hole Fermi quasilevels splitting there, $\Delta\Phi_{cv}$. Since $\Delta\Phi_{cv}$ remains nearly constant during lasing, most of the change in the bias voltage V_2 are directly reflected into a change of the voltage drop over the launcher, $V_2 - \Delta\Phi_{cv} e$, and, ultimately, in variation of injected electron energy. Hot electrons entering the AR are scattered by thermalized carriers and lose their energy, increasing the temperature of the thermalized sea. Thus any variation of the energy yield associated with a single injected electron, ϵ_C, that is the electron contribution to ϵ_J, results in a corresponding change in the effective temperature of the electron-hole plasma as a whole. This provides a way for a fast (on a picosecond time scale) gain switching using modulation of carrier temperature by a variation of ϵ_C. Particularly, if the stationary value is high enough to suppress lasing by carrier heating coupled to carrier injection,[16] a laser can be switched on by lowering ϵ_C and then switched off again by raising ϵ_C.[11,17]

A modeling example of the pulse generation by this modulation scheme is shown in Fig. 2. The approach used to describe lasing is based on the earlier reported model of an LD as a nonequilibrium system consisting of the injected carriers, the longitudinal optical phonons and the guided photons, interacting with each other.[9,18] The carrier injection rate, *J*, is assumed constant, and therefore, the gain-switched optical pulse is only the result of changing the energy injection rate, $Q = \epsilon_J J$, that is achieved by varying the energy ϵ_C. The alternative part of the latter is driven as $-\cosh^{-2}(t/\tau)$ with a time constant, τ, ensuring 10 ps half-width at half-maximum of a dip in $\epsilon_C(t)$. In agreement with the above-given estimate, 0.87 meV cooling of a thermalized electron-hole plasma inside an AR requires around 1 eV reduction in the injected electron energy. However, the resulting pulse is quite intensive, as can be seen from Fig. 2, and the peak value of the optical power, accounted per unit square of AR at a facet,[9] exceeds 10 mW/μm^2.

To investigate the injected electron energy as a function of the drive voltage an adequate description of the hot electron transport across the multivalley semiconductor heterostructure is necessary.[19] Here, as a first step, it is assumed that the energy distribution of electrons into the InGaAsP launcher is Maxwellian and spatially uniform. Then, Γ-L nonparabolic conduction band model is used for this layer. The spectrum of electrons in Γ and four equivalent L valleys being taken in a form as $\hbar^2 k^2/2m_i = \epsilon_i(1+\alpha_i \epsilon_i) \equiv \gamma_i(\epsilon_i)$,[20] $i = \Gamma,\ L$, with k as the wave number, referred to the minimum of a valley; m_i, ϵ_i, and α_i as the effective mass, the energy, and the parameter of nonparabolicity, respectively. The energy distribution in each valley is described by the same effective temperature, *T*, which is determined from the energy balance equation under the homogeneous drift conditions:

$$\mu(T)F^2 = w(T), \tag{1}$$

where $\mu(T)$ and $w(T)$ are the mobility and the energy relaxation rate per one electron, $F = (V_2 - \Delta\Phi_{cv}/e)/d_L$ and d_L are the electric field and the width of the launcher, respectively. Once *T* is found, ϵ_C, defined as energy to carrier flux densities ratio at the edge between the launcher and the AR, is given by

$$\epsilon_C = \frac{(1+3\alpha_\Gamma T(\Delta_C+2T)+P_{L\Gamma}(T)(1+3\alpha_L T)(\Delta_C+\Delta_{L\Gamma}+2T)}{1+2\alpha_\Gamma T+P_{L\Gamma}(T)(1+2\alpha_L T)}. \tag{2}$$

Here, Δ_C is the conduction band discontinuity, $\Delta_{L\Gamma}$ is the energy gap between L and Γ valleys into the launcher, and $P_{L\Gamma}(T)=4(m_L/m_\Gamma)\exp(-\Delta_{L\Gamma}/T)$. When deriving this formula, only the transitions in real space between equivalent valleys are taken into account,[19,21] and scattering by thermalized carriers is considered as the dominant energy relaxation process for hot electrons entering the AR. Then, the mobility and the energy relaxation rate in Eq. (1) are the weighted averages:

$$\mu(T)=\frac{\mu_\Gamma(T)+R_{L\Gamma}(T)\mu_L(T)}{1+R_{L\Gamma}(T)}; \qquad w(T)=\frac{w_\Gamma(T)+R_{L\Gamma}(T)w_L(T)}{1+R_{L\Gamma}(T)}, \tag{3}$$

where $\mu_\Gamma(T)$, $w_\Gamma(T)$, $\mu_L(T)$, and $w_L(T)$ are the contributions from Γ and L valleys, respectively, and $R_{L\Gamma}(T)=4[\aleph_{sL}(T)/\aleph_{s\Gamma}(T)]\ \exp(-\Delta_{L\Gamma}/T)$, with $\aleph_{si}(T)$ as the temperature-dependent density of states, in a case of nonparabolic band defined by

$$\aleph_{si}(T) = 2\left(\frac{2\pi m_i T}{(2\pi\hbar)^2}\right)^{3/2}\frac{1}{(\pi\alpha_i T)^{1/2}}\exp\left(\frac{1}{2\alpha_i T}\right)K_2\left(\frac{1}{2\alpha_i T}\right), \tag{4}$$

with $K_2(x)$ as a modified Bessel function of the second order. Since $K_2(x)\approx(\pi/2x)^{1/2}\exp(-x)$ for $x\gg1$, Eq. (4) is reduced to the usual $\aleph_{si}=2[2\pi m_i T/(2\pi\hbar)^2],^{3/2}$ if nonparabolicity can be neglected. When calculating $\mu_i(T)$ and $w_i(T)$, $i=\Gamma,\ L$, all the relevant intravalley and intervalley scattering processes are taken into account, in a way, similar to that used in the conventional Monte Carlo simulations.[20] Doing so, the nonparabolicity of conduction band is successively involved throughout (e.g., in calculation of the overlap integral from Bloch functions, etc.) and the evident shape of the distribution function is essentially used to obtain the macroscopic transport characteristics of hot electrons.[17]

The computed value of ϵ_C is plotted in Fig. 3 as a function of the voltage drop over the launcher, $V_2-\Delta\Phi_{cv}/e$. By comparing these data with the ones shown in Fig. 2, it is seen, that variable joule heating in the launcher is able to change the injected electron energy in a range necessary for generation of high-intensity T_e-switched pulses. Note that ϵ_C is not sensitive to the emitter-base bias voltage, V_1. The latter influences only the concentration of hot electrons into the launcher, through the control of J, but not their effective temperature. However, both bias voltages, V_1 and V_2, can be coherently driven in a way to provide the complementary modulation of carrier concentration and effective temperature that ensures suppressing of carrier related chirp along with pulse shaping.[6] Another important feature is that the drift of electron over the launcher is carried out at a given current density (controlled by V_1) and at a given electric field (controlled by V_2). This eliminates instability even though drift velocity, as a function of F, has a falling section caused by Hilsum–Ridley–Watkins mechanism.

In conclusion, a novel three-terminal laser structure is proposed and modeled, which is shown able to generate high-intensity picosecond optical pulses by gain-switching using variable carrier heating. This structure employs the standard, for InP-based devices, design of heterostructure bipolar transistor and LD and, therefore, is within reach of today's technology.

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