Hot Electron Injection Laser: Vertically Integrated Transistor-Laser Structure for High-Speed, Low-Chirp Direct Modulation

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The first Hot Electron injection Laser (HEL), a vertically integrated transistor-laser structure, is designed to investigate and possibly utilise carrier-heating effects on the optical gain and wavelength chirp. Simulations show the potential of carrier-heating assisted gain-switching to directly modulate the optical field intensity at frequencies up to 100GHz and to decrease the wavelength chirp. Lasing has been observed for the first time now at 70K, with a threshold current density of about 1.7kA/cm^2, from the current AlGaAs/GaAs HEL with InGaAs bulk active layer, indicating sources of excess internal absorption and/or (radiative) recombination.

Introduction

The performance of light sources used in high bit-rate optical communication systems is strongly affected by heating, and cooling, of the electron-hole plasma inside the active region. Both modal gain and index are affected by the carrier heating. Carrier heating effects in electro-optical semiconductor devices are being researched, for example, through optical pump-probe experiments on semiconductor optical amplifiers [1], short cavity and vertical cavity surface emitting lasers [2]. Tunneling injection lasers try to avoid carrier heating by tunneling electrons directly into the active region [3], leading to a "colder" carrier distribution and thereby minimizing hot-carrier related problems.

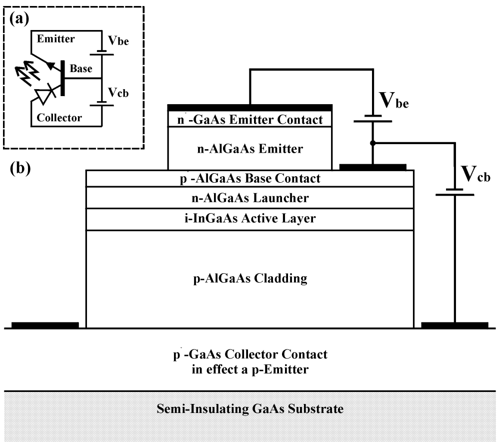


Figure 1: *(a) Electrical equivalent circuit and (b) schematic design of the vertically integrated transistor-laser structure*

This project, on the contrary, focuses on utilizing the carrier-heating effects to increase the modulation bandwidth while decreasing the wavelength chirp [4]. The carrier density and temperature affect the gain and the index in an opposite manner and relax on different time-scales. This suggests the idea to employ the quickly relaxing variations of carrier temperature for high-speed modulation of the laser output and to use the more slowly relaxing variations of carrier concentration to suppress the associated parasitic effects like relaxation oscillations and chirping of the emitted wavelength. Different mechanisms for direct and indirect carrier heating have been investigated by others. Gorfinkel et al [5] accomplished controlled carrier heating in a conventional semiconductor laser through a lateral microwave electrical field using two additional top-side ohmic contacts. They showed that carrier heating can strongly influence the optical output.

Hot electron injection mechanism

Independent modulation of both carrier concentration and temperature can be accomplished by means of a novel vertically integrated transistor-laser structure [6], in which the electrons are injected into the active region of the laser with a certain excess energy [Fig. 1]. This design basically resembles an npn heterojunction bipolar transistor with the active region of a laser and a p-type cladding replacing the collector. The injected carrier current is controlled by the voltage Vbe applied to the emitter-base junction. The voltage Vcb applied between the ‘collector’ and base contacts falls mainly across the low doped n-AlGaAs ‘launcher’ region, resulting in a controllable transverse electric field heating the electrons and injecting them into the active layer where the excess energy is redistributed through carrier-carrier interactions [Fig. 2].

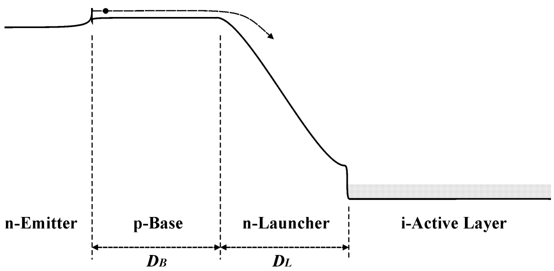
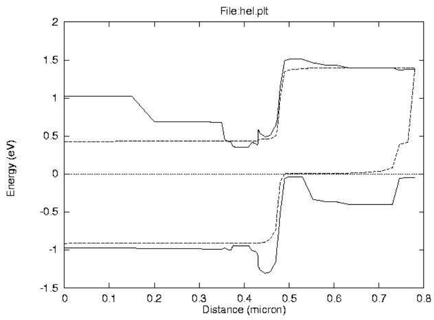


Figure 2: *Schematic conduction band energy diagram of the electron injection structure*

Simulating the carrier transport

Commercial device simulators were used to simulate the L-I-V behavior. Figure 3 shows the simulated energy band diagram under bias. Electrons are injected from the emitter at the right across the base towards the base-launcher junction. The conduction band energetic barrier here and the minority carrier lifetime inside the base determine the injection efficiency of electrons across the base into the launcher with its high transverse electric field. The electron injection efficiency is strongly dependent on the applied collector-base (CB) voltage. The applied voltage falls mainly across the low doped launcher region, thereby decreasing the conduction band energetic barrier between base and launcher. The injection efficiency increases with increasing CB voltages to remain fairly constant for CB voltages greater than about 0.4V. The applied CB voltage also decreases the valence band barrier between active region and launcher thereby triggering a hole leakage current from the active region across the launcher and into the base. The operating range for the laser is therefore between about 0.5 and 1.5V. Both the emitter current (carrier concentration) and the collector-base voltage (carrier temperature) can control the optical intensity independently in this range.



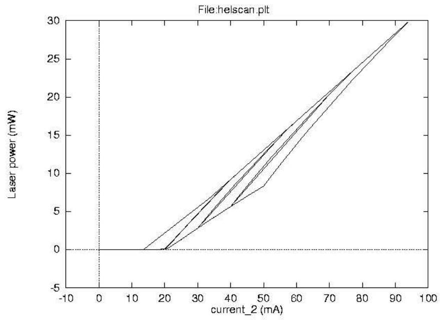
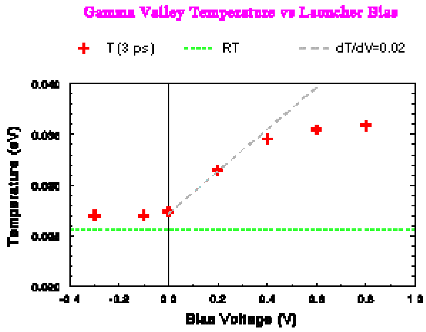


Figure 3 [left]: *Simulated energy band diagram under bias. Left: collector. Middle: active layer (0.4μm), launcher (0,45μm) & base (0,5μm). Right: emitter.*

Figure 4 [right]: *Simulated optical power vs. emitter current. Lower diagonal curve: Vcb=0V. Upper diagonal curve: 0.4<Vcb<1.5V. Connecting curves: 0<Vcb<0.4V*

Monte-Carlo particle simulations are used to simulate the 1D electron transport across the crucial regions base, launcher & active region. Figure 5 shows an effective carrier temperature change of 10meV per volt bias Vcb, sufficient to switch off the laser. At first the carrier temperature follows a slope of 20meV/V but saturation occurs at higher CB voltages. Furthermore, the switching transient lasts only a few picoseconds, allowing very high-speed modulation [Fig. 6].



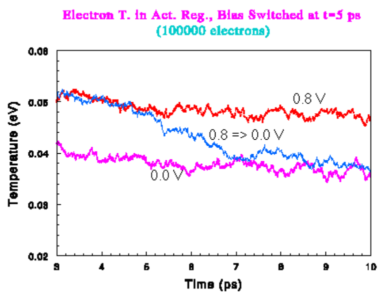


Figure 5 [left]: *Monte-Carlo simulation of the electron temperature in active region vs collector-base bias Vcb*

Figure 6 [right]: *Monte-Carlo simulation of the transients after switching off Vcb. Upper: Vcb=0.8V. Lower: 0.0V. Connecting trace: switched at 5ps from 0.8V to 0.0V.*

Measurements

The epitaxial wafers were grown by at the I.S.I. in Jülich using MBE and processed using the cleanroom facilities in Eindhoven. Unexpectedly, low collector-base voltages result into a poor electron injection efficiency from the base into the launcher. The injection efficiency gradually increases with an increasing CB voltage. A hole leakage current from the active layer, through the launcher, into the base becomes dominant at even higher CB voltages. The optical characterization at room temperature shows only spontaneous emission for injection currents up till 20kA/cm2. The spectrum shows one peak corresponding to the InGaAs bandgap. The absence of other peaks indicates that the radiative recombination in the base is negligible. At 70K laser action is observed with a threshold current density of about 1.7kA/cm2 [Fig. 7]. Threshold current densities one would normally expect for stripe geometry lasers at 300K! Similar lasers at 100K have threshold current densities ten times as small, indicating unknown sources of excess internal absorption or (radiative) recombination.

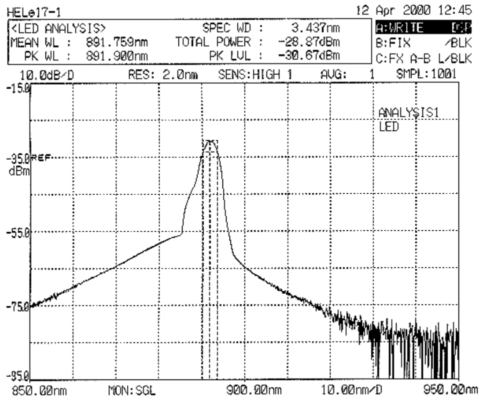


Figure 7: *Optical spectrum of a HEL lasing at 70K, centered around 892nm*

Conclusions

The vertically integrated transistor-laser structure, with potential to switch within only a few picoseconds, shows lasing at 70K for the first time. The high threshold current indicates unknown sources of excess internal losses and/or (radiative) recombination. Electron injection efficiency and the hole leakage current still need to be improved. Improving these is expected to lead to a hot electron injection laser lasing at room temperature, enabling direct measurements of the carrier heating effects on the optical gain and wavelength chirp in semiconductor lasers.

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