Electrical Derivative Analysis on Current Leakage in Buried-Heterostructure Lasers

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***Abstract*— A full 2-D simulation was performed to investigate electrical derivative characteristics of 1.3µm AlGaInAs/InP buried-heterostructure semiconductor lasers with different current leakage paths and to explain their physical root causes. The simulation results match with experimental data under several different cases, and therefore could be used as guideline to explain device performance without any destructive failure analysis. Parameters extracted from electrical derivatives could be used as screening to catch devices with inferior performance and potential reliability risk.**

Keywords—simulation, buried-heterostructure, semiconductor laser, current leakage

I. Introduction

1.3µm buried heterostructure lasers fabricated from AlInGaAs/InP quaternary material system have been widely used in high-speed fiber optical transmission systems with benefits of low threshold current and reduced temperature sensitivity. A 3dB bandwidth of 55GHz has been reported from a short-cavity distributed reflector laser with conventional PN blocking structure [1]. However, the imperfect fabrication could generate severe current leakage paths and affect device performance and long-term reliability.

Scanning electron microscope (SEM) can be used to sampling examine actual devices to evaluate quality of PN blocking structure, however it is a destructive approach and cannot be applied to each individual device, and it does not reveal leakage path along layer interfaces.

Electrical derivative characteristics have been investigated using equivalent circuit models by Wright [2]. The product representation *IdV/dI* yields a plot with series combination of linear resistor and nonlinear resistor with exponential characteristic of an ideal *PN* junction. It was also demonstrated that electrical derivatives at initial test could be used to predict rapid aging devices [3]. However, the lumped circuit model was too simplified and the nature of the leakage paths could not be physically explained in depth.

A comprehensive 2-D laser model needs to be established to generate more realistic electrical derivative performance to match with actual geometry based on SEM image. It can provide physical explanation on the distribution of carriers and how the different current leakage paths are formed, without any destructive method.

II. Model

The BH laser was analyzed using a commercial 2-D laser simulator LASTIP, which has demonstrated meaningful results on carrier and photon distribution of such lasers [3]. It simulates the laser characteristics by solving Poisson's equation, the current continuity equations for electrons and holes, and the wave and rate equations numerically by the finite element analysis.

The laser structure has compressively-strained InGaAlAs MQW material in 1.2µm active-region mesa, surrounded by InP epitaxial layers. A conventional reverse biased PN blocking structure, adjacent to the active mesa, confines current to flow through active region, shown in Fig. 1(a). By confining current in this manner, low threshold and excellent optical beam characteristics can be obtained. However, several current leakage paths allow current flow through the PN blocking structure, resulting into increased threshold, reduced quantum efficiency.

The definition of parameter extraction from the characteristics is based on the equivalent circuit model in literature [2], shown in Fig. 1(b). The junction ideality factor *n* is defined as the intercept of subthreshold portion of the *IdV/dI* characteristic. The sudden dip *h* at threshold indicates the expected saturation of the junction voltage at threshold. Other parameters include zero current intercept of the curve above threshold *b*, threshold *Ith*, and series resistance *R*s.

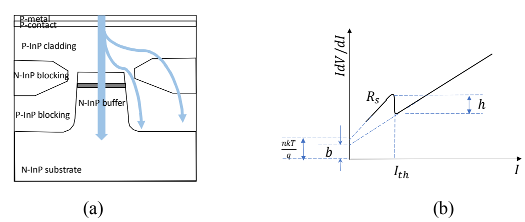

Fig. 1. (a) Schematic diagram of transverse cross-section of a BH laser with conventional PN blocking structure. (b) Definition of parameter extraction from electrical derivative characteristics.

III. Results

In this paper, three different cases of leakage paths are studied. The model of a typical device is first established as baseline.

A. Gap between n-blocking and mesa

The first case study is a BH laser in which the first regrown P-InP layer has completely overgrown the mesa, leading into a big gap between N-InP blocking layer and mesa, shown in Fig. 1(a).

Figure 2 shows the electron distribution and electrical derivative product representation *IdV/dI* analyzed from the L-I-V raw data generated by the simulator. The first curve represents an ideal laser with no leakage path, where the curve is completely linear both below and above threshold. The second curve represents a typical BH laser with small gap around 0.1µm wide. The third curve represents the case with a large 0.5µm gap of N-InP blocking layer. Both portions below and above threshold show increase of curvature, which indicates significant parallel path for current flow. Both simulated curves match well with experimental data from lasers with similar cross-section geometry.

LASTIP simulation indicates that there is a high density of holes populating into the gap, which greatly reduces the potential barrier between N-buffer and P-blocking layer. Therefore, electrons can overflow from N-buffer, through the whole PN blocking layers, arrive at P-cladding layer and generate great spontaneous emission.

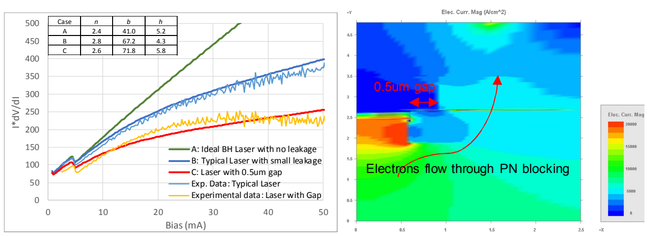

Fig. 2. Simulated electrical derivative characteristics of BH laser with and without gap between N-blocking and mesa.

B. *N-Blocking Layer Touching Mesa*

The second case study is a BH laser with insufficient P-InP blocking material and therefore the second regrown N-InP layer severely touching top section of the mesa. *IdV/dI* shows severe impact on the curve above threshold, while the subthreshold session does not change. Because the top section of mesa is p-type doped, certain voltage is required to turn on the diode and create the leakage path. Once the diode turns on, the shunt leakage path dominates, leading to more linear curve at high bias. LASTIP simulation at high bias indicates a severe electron flow from N-buffer layer to N-InP blocking layer through the edge of the mesa sidewall. The extracted *b* value increased drastically due to the severe shunt leakage.

C. *Nonlinear Leakage through PN Blocking Thryistor*

The third case study is a BH laser in which the doping level of P-blocking layer is unintentionally much lower than the target of 1e18 cm^{-3}. With 4e17 cm^{-3} doping level, the potential barrier is not high enough between N-buffer and P-blocking layers, and electrons are able to overflow across the barrier to reach P-clad under high bias and generate huge radiative spontaneous emission far apart from the active layer, already experimentally approved by EL measurement in [4]. Therefore, the PN junctions with insufficient barrier under reverse bias exhibits an exponentially increasing leakage current under high bias.

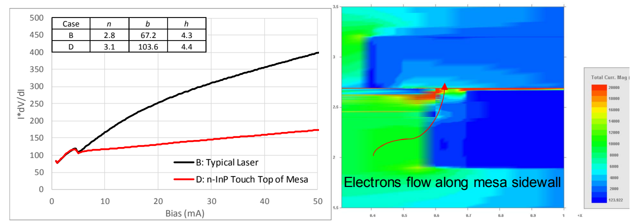

Fig. 3. Shunt leakage due to n-blocking layer touching the active region.

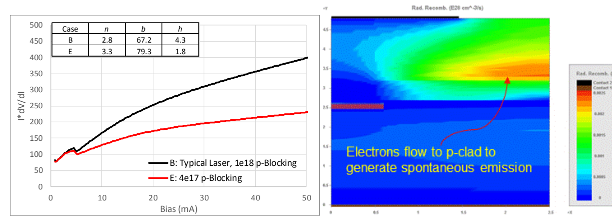

Fig. 4 Simulation on BH laser with different doping levels in N-blocking

Among all three cases, the second case of N-InP blocking layer touching mesa has the most severe impact to performance, especially under normal operation condition (intermediate bias). Cases with large gap or low P-blocking doping show more nonlinearity above threshold, indicating nonlinear leakage path through PN blocking.

Analyzing extracted parameters reveals that increased *b* affected by above-threshold curvature and reduced threshold step *h* indicate nonlinear path for current flow. Parameter *b* is extracted based on curve right above threshold, which may underestimate nonlinearity at high bias range. In order to capture all the leakage modes, more than one parameters need to be defined and applied to form a thorough screening scheme.

IV. CONCLUSIONS

A full 2-D simulation was first time established to evaluate different current leakage paths and corresponding electrical derivative characteristics in 1.3µm AlInGaAs/InP BH lasers. Specific parameters extracted from *IdV/dI*, like intercept *b* and threshold step *h*, be used to screen out devices with noticeable current leakage. Without any destructive analysis, we can establish a solid characterization system to capture devices with inferior performance and potential reliability risk.

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