Scanning Voltage Microscopy on Buried Heterostructure Multiquantum-Well Lasers: Identification of a Diode Current Leakage Path

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***Abstract*—We report scanning voltage microscopy (SVM) results on actively driven buried heterostructure (BH) multi-quantum-well (MQW) lasers that exhibit current blocking failure at high current injection operation. The measured two-dimensional image of local voltage distribution delineates the buried structures of the BH laser. The results, in combination with light–current–voltage (L–I–V) measurements, connect macroscopic external performance to measurements on the nanometer scale. Our experimental results suggest that the current blocking breakdown observed in the MQW BH lasers correlates with the turn-on of a diode leakage path when the devices are biased at high current injection.**

***Index Terms*—Atomic force microscopy, fault diagnosis, leakage currents, microscopy, semiconductor device breakdown, semiconductor lasers.**

I. Introduction

Buried heterostructure (BH) multiquantum-well (MQW) lasers have low threshold currents and a stable fundamental transverse optical mode due to tight confinement of carriers and photons to an active region defined by the current-blocking structure [1]–[6]. Semiconductor layers with alternating doping types, i.e., p-n-p-n blocking structures, are often deployed for lateral current confinement in BH lasers [7], [8]; however, the leakage current, which increases with temperature and injection current, results in deterioration of the performance of the laser [9], [10].

In BH lasers with p-n-p-n blocking structures, two leakage current paths outside the active region—the diode leakage current and the thyristor leakage current—influence laser performance [4], [11]. Fig. 1 shows a schematic transverse cross section of the BH laser and the possible leakage current paths. The "diode leakage" current (I_{L1}) flows through the p-InP cladding layer, p-InP blocking layer, and n-InP substrate. The "thyristor leakage" current (I_{L2}) flows through the p-InP cladding layer, n-InP blocking layer, p-InP blocking layer, and n-InP substrate.

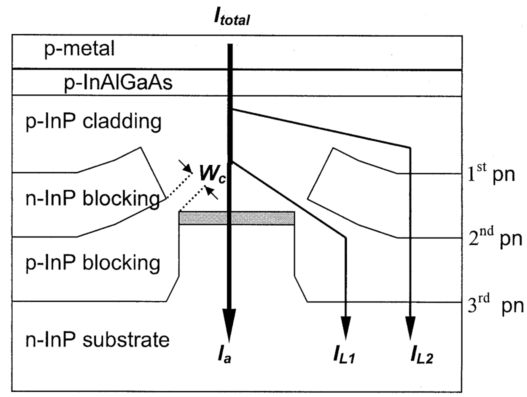

Fig. 1. Schematic transverse cross-sectional structure of a BH laser showing the possible current paths from p- to n-sides. W_c is the minimum distance between the active region (shadow area) and the n-InP blocking layer and is referred to as the connection width.

Investigations based on a simplified equivalent electrical circuit calculation show that the connection width (W_c), as defined in Fig. 1, plays a key role in determining the current leakage [11]. Blocking of the current path (I_{L1}) between the p-cladding and p-blocking layers was revealed in our previous SSRM and SCM studies of BH MQW lasers at equilibrium [8]. The depletion regions between p- and n-doped InP layers near the active region/p-n-p-n blocking structures interface are crucial in funneling current into the active region. The diode leakage current can be minimized by enhancing the depletion width and hence reducing the connection width [9].

As the BH laser device is biased at a high injection current, a forward breakover of the current-blocking structures is often observed [12]. Previous experimental studies of the current blocking breakdown phenomena have consisted of characterization of external performance measurements such as light–current–voltage of device under working conditions [13], experimental investigations involved with electron beam-induced current (EBIC), and transmission electron microscopy (TEM) measurements on the transverse cross section of devices at equilibrium state [14]–[16]. Direct observation of the internal voltage distribution in a lasing device is an important step to resolving where the failure of lateral current blocking occurs.

In this paper, we report results of two-dimensional (2-D) local voltage measurements of the transverse cross section of operating BH MQW lasers using scanning voltage microscopy (SVM). The measured 2-D image of voltage distribution clearly

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resolves the buried MQW active region and the current-blocking p-n-p-n structures of the BH lasers. The SVM measurements were performed on the p-n-p-n current-blocking region and the active region of the BH laser devices under various forward bias voltages. Special attention was focused on the current-blocking breakdown—a practically important problem associated with the high-power operation of some BH lasers and a potential case of failure mode analysis. SVM results on actively driven devices show that the turn-on of the diode leakage path appears to correlate with the breakdown of the current-blocking structure.

II. Experiment

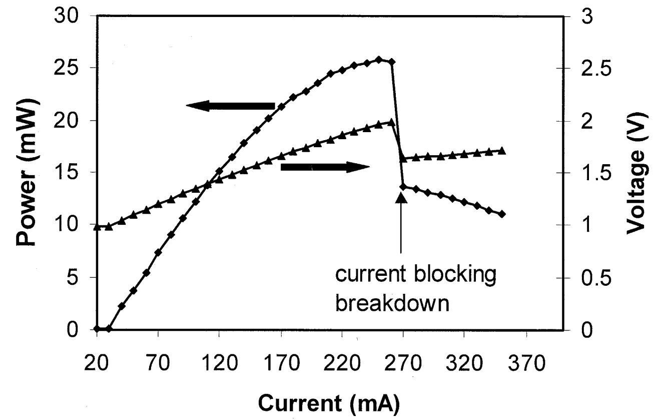
The experimental setup and procedure of the SVM measurements can be found in [17] and [18]. The measurements were performed on an atomic force microscope (AFM) [Digital Instrument (DI), Dimension 3100] by using the commercially available boron-doped diamond coated cantilever tips (DI, DDESP) [19]. A conductive AFM probe was scanned in contact mode over the cross section of the laser devices. The voltage signal from the conductive probe was measured by a voltmeter with high input impedance (Keithley 6517 A) and acquired by the AFM computer (DI, Nanoscope IIIa) via a signal access module (DI). The voltmeter offers an accuracy of 10 μV in voltage measurement. Fluctuations in the measured voltage were observed in our experiments to be around 50 mV. The lasers under test were driven by applying variable forward bias voltages. A precise current source (LDX 3412, ILX Lightwave) was used to bias the laser within an accuracy of 0.1 mA. The AFM tip scan rate varied from 0.004 to 0.5 μm/s, depending on the spatial resolution required of the measurements. The contact force was set high enough such that the tip mechanically penetrates the native oxide layer at the sample surface to establish a good electrical contact.

The MQW active region of the BH (InGaAsP–InP) lasers was grown by metal–organic chemical vapor deposition (MOCVD). The mesa of the laser is buried beneath a four-InP-layer structure with alternating doping type. The laser samples were metallized on both sides to produce ohmic contacts. The current–voltage (I–V) characteristics of the laser devices were measured before, during, and after the SVM experiment. No change was observed in device electrical behavior.

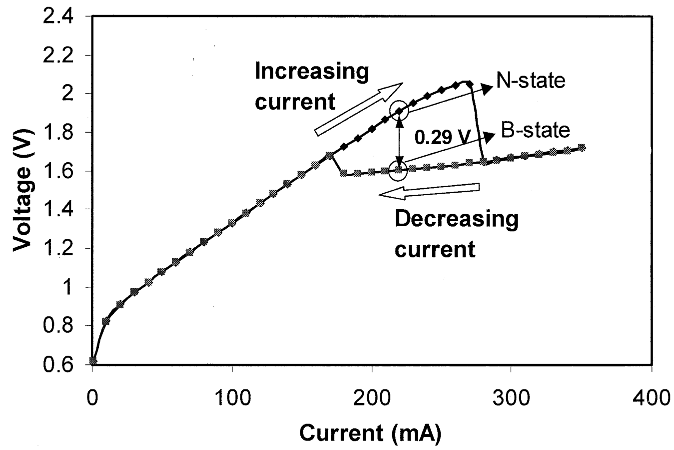
III. Results and Discussion

Fig. 2(a) shows the light–current–voltage (L–I–V) characteristics of a BH laser which exhibits breakdown of the current-blocking structure at a current injection of 270 mA. The applied voltage and the light output drop sharply as current injection rises above the breakdown point. This indicates that at least one current leakage path had turned on and a significant portion of the injected current had bypassed the MQW active region. As a consequence, the applied voltage dropped from 1.985 to 1.635 V and the optical output power degraded from 25.6 to 13.6 mW.

Fig. 2(b) shows the hysteresis phenomenon in the breakdown of the current blocking. The current leakage path was turned on when increasing current injection to 270 mA and turned off when decreasing current injection to 170 mA. The IV curves were repeatable with cycling, which indicates that the breakdown of the current-blocking structure was not due to permanent physical damage of the device. Similar phenomena were observed on a collection of BH lasers.



(a)



(b)

Fig. 2. (a) L–I–V curves of a typical BH laser which shows the breakdown of current blocking. (b) IV curves of the BH laser with cycling the current injection, showing the hysteresis behavior of the current blocking failure. The state in which the leakage current was turned on is denoted by B-state; the state in which the leakage current was turned off is denoted by N-state.

Fig. 3 shows a typical 2-D SVM voltage profile. The laser was under a dc forward bias of 0.920 V, which was above lasing threshold. The buried mesa is clearly resolved in the SVM image. The narrow strip at the left side of the mesa in the SVM image is the MQW active region, clad by p- and n-doped layers from the left and right. At the top are the p-n-p-n current-blocking structures. The accumulated voltage change from the p-metal to the n-doped substrate measured from the SVM is 0.913 V, in good agreement with the external voltage applied to the device.

The internal voltage profiles of the BH laser under the normal state (denoted hereafter as N-state) and the breakdown state (denoted hereafter as B-state) were measured using SVM. At first, SVM cross-line scans were performed on the p-n-p-n region that was away from the mesa structure of the laser. The device was operating in the N-state and B-state, respectively, but at the same current injection of 220 mA. As labeled in Fig. 2(b), the externally applied biases differed by $\sim$ 0.29 V in these two states.

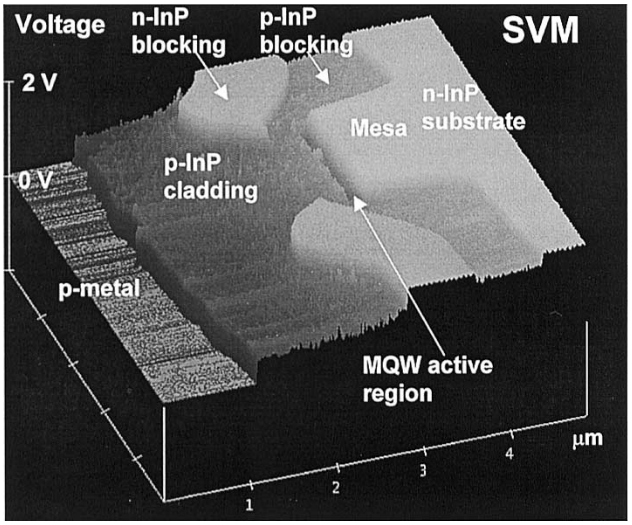


Fig. 3. Two-dimensional SVM image of a BH laser under forward bias of 0.92 V. The scan rate was 0.005 Hz.

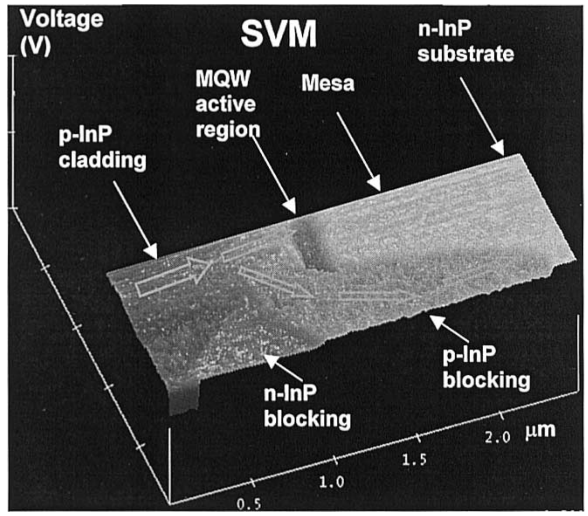


Fig. 4. Two-dimensional SVM image of the transverse cross section of an actively biased BH laser in the vicinity of the diode leakage path. The laser, biased at 190 mA, was in the B-state.

TABLE I
SVM Measured Voltage Differences at Interfaces and pn Junctions (see Fig. 1) Across the p-n-p-n Structure as the BH Laser Was in the N-State and the B-State. The Current Injection Was $I = 220$ mA

Voltage drop (V)	p-metal-p-InP	1st pn	2nd pn	3rd pn
N-state	0.783	0.133	0.475	0.079
B-state	0.713	0.100	0.319	0.176

Table I presents the voltage drops at the semiconductor interfaces as measured in the SVM line scans. Most of the voltage change occurred at the p-metal-p-InP interface and the second pn junction from the device top surface in both cases. Due to the decrease of the external bias required for the given current injection (220 mA), the voltage drops at the p-metal-p-InP interface and the first pn junction in the B-state were modestly smaller than those in the N-state, respectively. The biggest reduction in voltage drop (0.156 V) was observed at the second pn junction, which was under reverse bias [17] and hence counted for most of the bias change. The voltage profiles across the p-n-p-n structures in the B-state and N-state, even though different in quantity, remain qualitatively similar. The increase of voltage drop at the third pn junction, as switching from the N-state to the B-state, will be further discussed below.

Fig. 4 shows a 2-D SVM image of the cross section of an actively biased BH laser. The laser was biased at 190 mA and was in the B-state. The figure shows a smooth transition in voltage from the p-InP cladding to p-InP blocking layers across their adjoining area, near the mesa structure. This indicates a current path between the two p-doped InP layers, as denoted by arrows. As a consequence, the injected current could partly flow through the p-InP cladding layer, p-InP blocking, and n-InP substrate rather than channeling to the MQW active region. Here lies the diode current leakage path (I_{L1}).

The diode current path through the adjoining interface between the p-InP cladding and p-InP blocking layers is pinched off under normal operation conditions (i.e., the N-state). Even though the two p-InP layers are physically connected, the electrical connection is blocked by depleted regions near the corners of the mesa structure. This was visualized in the SCM closed-loop amplitude mode image [8] and is confirmed with the following analysis. The total depleted width of the junctions near the MQW active region/p-n-p-n blocking structures interface is estimated to be on the order of 200 ± 40 nm. This is comparable to the connection width, which is $W_c =\sim 260$ nm as measured from an SSRM image of the transverse cross section of the laser.

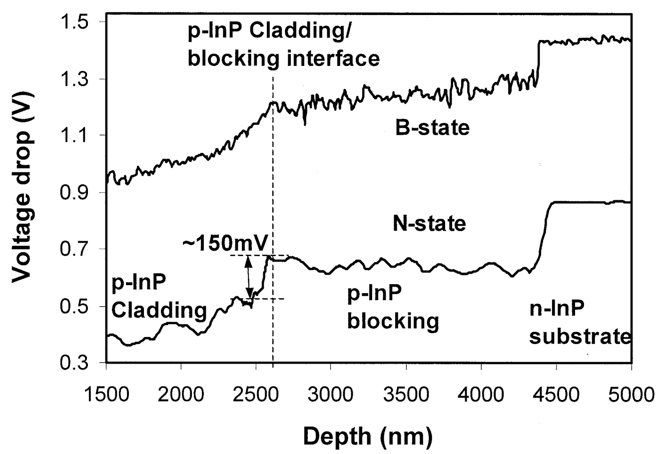


Fig. 5. Comparison of the cross-sectional voltage profiles along the p-InP cladding, p-InP blocking, and n-InP substrate (diode leakage path, $L1$) as outlined in Fig. 1 when the laser was in the B-state and the N-state.

With increasing current injection and thus external bias voltage, the forward bias applied on the pn junctions (the first and the third from the top) increases correspondingly. This leads to the shrinking of the depletion region of the pn junctions, a phenomenon revealed on SVM on a pn junction [18]. As the device bias rose beyond the point at which the combined depletion width was considerably smaller than the connection width, the two p-InP layers connected electrically with each other, opening the diode current leakage path.

Fig. 5 shows the cross-sectional analysis of voltage profiles along the diode leakage path ($L1$) as depicted in Fig. 1. An abrupt voltage change ($\sim$ 150 mV) at the p-InP cladding/p-InP blocking interface was observed along the diode leakage path in the N-state. When the diode leakage path opened, the voltage profile varied smoothly across the interface in the B-state curve. This correlates to the current blocking failure as the device was under high current injection.

When the device was under forward bias, the first and the third pn junctions of the p-n-p-n structure were under forward bias as well. The change of the voltage differences across the junctions is therefore a sign of the change of the current flowing through the interfaces. As revealed in Table I, when the laser was switching from the N-state to the B-state, the voltage drop at the third pn junction increased from 0.079 to 0.179 V. This could indicate a significant increase of current flow through the p-InP blocking/n-InP substrate interface. On the contrary, the voltage difference at the first pn junction showed no increase but a small decrease.

The combination of thermal effects resulting from active region heating and high electrical field across the p-n-p-n blocking structures under high current injection are most likely to be responsible for the observed turn-on of the current leakage path. At high current injection, the temperature of the active region as well as the neighboring p-n-p-n structures may be considerably higher than the heatsink temperature. The temperature increase gives rise to generation of more excess carriers in the intrinsic and/or depleted regions, which results in more current leakage. Elevated internal electrical field leads to an increase of field emission or tunneling current through the regions where no current should flow ideally.

Our SVM results show direct experimental evidence for the turn on of the diode leakage path at high current injection in the BH laser samples. The combination of SVM and L–I–V results points up the correlation between the observed current blocking failure and the diode leakage. The appearance of the increased current leakage as revealed in light-voltage-current measurements [Fig. 2(a) and (b)] is attributed to the reduction of the depletion width of the connection channel between p-cladding and p-blocking layers. Due to the interplay among carriers, current, and voltage, the breakdown of the depletion may give rise to some more complex leakage current flow, i.e., current flow through the "thyristor leakage" path. It has been found that the thyristor leakage could occur locally—only in part of the p-n-p-n blocking structure—along the longitudinal direction of the laser cavity and away from the facets being probed [20]. It is possible that the thyristor leakage could be partially induced by the diode leakage current. Further investigations would be required to resolve these questions fully. The SVM method deployed in this study assists in diagnosing the origins of externally-observed active optoelectronic devices such as lasers, modulators, and detectors.

IV. Conclusion

Two-dimensional SVM was used to profile the transverse cross-sectional potential distribution in MQW BH lasers under operating biases, resolving the MQW active region, p-n-p-n blocking structure, and the mesa structure in two dimensions. The SVM results suggested the turn-on of a diode leakage path, which correlated with the observed current-blocking breakdown as the device is biased at high current injection. Our results demonstrate the utility of 2-D SVM to delineate quantitatively the transverse cross-sectional voltage and potential profiles of complex 2-D devices—such as functional BH MQW lasers—under operating conditions.

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