Ion-Implanted GaAs–InGaAs Lateral Current Injection Laser


Abstract—We have fabricated and characterized lateral current injection (LCI) ridge-waveguide lasers formed by ion-implanted injectors. Comprehensive optical and electrical measurements have been performed over a wide temperature range (10 K–300 K) on two sets of lasers with differing ridge widths and active region structures. Several new phenomena unique to the LCI mechanism have been observed, including a positive differential resistance kink at threshold, and inverse temperature-dependencies of quantum efficiency and threshold current at cryogenic temperatures. Electron–hole mobility disparity, local carrier nonpinning above threshold due to photon-assisted ambipolar diffusion, and intrinsically higher current densities have been identified as the major factors governing these LCI laser characteristics. The results have important implications for future LCI laser design and ultimate performance.

Index Terms—Integrated optoelectronics, ion implantation, optoelectronic devices, semiconductor device fabrication, semiconductor device modeling, semiconductor device ion implantation, semiconductor lasers.

I. INTRODUCTION

LATERAL current injection (LCI) lasers [1], with both p- and n-contacts on top of the structure and current flowing along the quantum wells (QW’s), have considerable advantages over more traditional vertical current injection (VCI) devices: they are inherently suitable for planar optoelectronic integration, offer greater compatibility with field-effect transistors, and free the vertical dimension for control (e.g., gating) of laser operation and implementation of novel device functions.

The lateral injection approach also offers a possible solution to a known problem of multiquantum-well lasers (MQW’s): nonuniform carrier and gain distributions among the QW’s. This vertical nonuniformity stems from the efficient capture of holes by the first QW’s adjacent to the p-injector, and effectively limits the number of QW’s which can be incorporated into the active region of a VCI laser. The LCI approach overcomes this problem by allowing parallel injection of carriers into all QW’s, allowing vertically uniform QW gain even with many QWs; this has many potential advantages, including the possibility of gain-coupled DFB VCSEL’s [2], [3].

However, significant use of LCI lasers has so far been impeded by two main factors: technological difficulties associated with formation of p+- and n+-contact regions (injectors); and the inferior lasing efficiency and threshold characteristics obtained so far, in comparison to the best VCI lasers. With the LCI geometry, contact regions are located aside the laser waveguide and must be specifically formed after the initial growth of the laser structure; they should provide not only electrical contacts to the active region, but also lateral confinement of carriers within the active region.

So far, injectors have been formed by either double regrowth to form p+- and n+-regions on each side of the active mesa [4], [5], or by impurity diffusion processes [6]–[8]. The former method has yielded generally lower thresholds and higher lasing efficiency, but is technologically very demanding. The latter process, involving selective high-temperature diffusion of Zn and/or Si ions into injector regions, is much simpler and has been used for laser fabrication for many years [9]. In the case of MQW active regions, it brings additional advantages originating from diffusion-induced disordering [10], which allows electrical and, to some extent, optical confinement in the lateral direction, without regrowth. However, the technology of dopant diffusion is imprecise for lateral junction formation, with serious attendant crosscontamination problems, and can highly complicate OEIC fabrication.

For this reason, ion implantation offers a better choice for contact region creation: it has much higher precision in both vertical and lateral doping profiles, does not lead to contamination problems, and has been a standard process in integrated circuit fabrication. The use of implantation-induced disordering of MQW waveguides has been proposed and actively investigated as a promising way to avoid regrowth in OEIC’s containing both active and passive elements [11], [12]. Creation of efficient LCI lasers by ion-implantation would thus constitute a significant step toward implementation of OEIC’s.

Our preliminary theoretical studies [1], [13] have shown that the ultimate performance of ion-implanted ridge LCI lasers, compatible with OEIC technology, can be at least as good, and in some aspects superior to that of VCI devices, if designed in accordance with the distinct operational physics of LCI devices. However, such a design requires in-depth knowledge.
of the parameters involved in complicated lateral photon-assisted bipolar transport in LCI lasers. This transport differs in many major aspects from vertical carrier transport in standard lasers, and has been considerably less investigated, either theoretically or experimentally, which greatly complicated LCI laser optimization.

In this paper, we describe the fabrication and characterization of what we believe is the first working ion-implanted LCI ridge-waveguide laser. We investigated the use of ion implantation for p⁺- and n⁺- contact region formation, and performed the first comprehensive analysis of a number of operational features (mechanisms) intrinsic and unique to the LCI laser. These include the disparity in in-plane transport of electrons and holes and their consequences for modal gain, threshold, and quantum efficiency; the issues of lateral carrier confinement, electron leakage and local carrier nonpinning due to photon-assisted lateral diffusion; and the nature and device consequences of high current density and longer current path across the active region.

II. Fabrication

Two laser structures, with similar Al₀.₇Ga₀.₃As claddings and differing core regions, were grown by MBE on semi-insulating GaAs: the first structure (LCI#1) was undoped and consisted of two 60-Å In₀.₅Ga₀.₅As QW’s, sandwiched between two 150-Å GaAs inner wave-guiding layers and separated by a 120-Å GaAs barrier layer; the second (LCI#2) had a p-doped (Be 5 × 10¹⁷ cm⁻²) active region consisting of three 100-Å In₀.₅Ga₀.₅As QW’s separated by 100 Å Al₀.₂Ga₀.₈As barriers, and sandwiched between two 400-Å Al₀.₂Ga₀.₈As inner wave-guiding layers. The p-doping in the second structure was intended to provide an additional supply of holes along the active region, in order to partly compensate for lower hole mobility and make the lateral gain profile more uniform.

The laser structures were patterned using a SiO₂ mask layer, and then dry-etched in an ECR chamber to form ridges as shown schematically in Fig. 1. Etching was monitored interferometrically [14] and stopped at ~40–60 nm above the MQW region. Since no etch-stop layers were employed, high-precision dry etching was important for making reliable ohmic contacts to the laser active layer, and thus for good laser performance. After ridge formation, the residual SiO₂ layer on the ridges was kept intact, and a thin (300 Å) Si₃N₄ capping layer was deposited by PECVD to protect the surface during future high-temperature annealing. Then Si ions were implanted (dose 4 × 10²³ cm⁻², ion energy chosen to yield maximum ion concentration in the MQW region) through photoresist openings to form n-doped contact regions. During implantaation, a combination of photoresist and the self-aligned residual SiO₂ layer atop the ridges was used to mask all of the structure except the first 10 μm on one side of the ridge, where the n⁺ injector was to be formed.

After the Si implantation, new openings were formed on the other side of the ridges in a new layer of photoresist, and p-contact regions were similarly formed via Be implantation, with a dose of 1 × 10¹⁵ cm⁻². This higher dose was used since Be is known to activate more easily at high doses than Si [15], and also to counterweight the high diffusivity of Be during high-temperature annealing [16]. This high Be diffusivity in fact served to shift the diffusion front (and thus the p-i junction) under the ridge during annealing, which is a design counter-measure to low hole mobility, suggested by our theoretical studies [1]. The implants were annealed simultaneously using RTA technique at 900 °C, which was optimized for maximum Si activation. Annealing time was chosen to obtain the desired lateral diffusion of Be under the ridge, and was typically 20–30 s. Finally, Au–Ge n-ohmic contacts and Mn–Zn (LCI#1) or Pd/Pt/Au (LCI#2) p-ohmic contacts were formed sequentially by liftoff on each side of the ridges. The samples were then thinned to ~150 μm, cleaved into individual devices of 300, 500, and 700 μm length, and mounted contacts-up on standard laser carriers.

To investigate the influence of lateral carrier transport on laser performance, sets of lasers with different ridge widths d were fabricated from each wafer, with d ranging from ~0.7 to 10 μm for LCI#1, and from ~0.7 to 2.8 μm for LCI#2.

III. Measurement Results

We have performed measurements over the broad temperature range of 10 K–300 K, including light versus current (L–I) characteristics in pulsed and CW regimes, optical spectra, far-field measurements and electrical characterization.

A. L–I Characteristics

The best lasers from both LCI#1 (undoped active region) and LCI#2 (doped active region) exhibited submilliampere threshold at cryogenic temperatures, with minimum values of 860 and 230 μA for 300-μm-long devices. Generally, the LCI#2 lasers performed much better than the lasers from LCI#1, which can be attributed in part to the higher vertical optical confinement factor for the former laser structure, and in part to the p-doping of the active region, as will be discussed below. However, both suffered from excessive contact resistance, which for 300-μm devices was typically around 15–25 Ω, and must be improved. To avoid effects from excessive resistive heating, most measurements were performed in the pulsed regime, with pulse duration 0.2 μs and 0.3% duty cycle. Figs. 2 and 3 show the typical temperature dependence of pulsed L–I characteristics of LCI#1 and LCI#2 lasers with 2-μm ridge width. The LCI#1 devices showed lasing only at
reduced temperature, with no lasing threshold observed above $T_{\text{max}} \sim 220$ K. However, LCI#2 devices performed reasonably well at room temperature, with $J_{\text{th}} = 45$ mA for the 300-$\mu$m lasers; the threshold increased to $\sim 55$ mA for 500-$\mu$m devices and $\sim 65$ mA for 700-$\mu$m devices, which corresponds to an internal optical loss of $\sim 16$ cm$^{-1}$.

We found that for both sets, laser performance generally improved with decreasing ridge width until a nominal value of $1$ $\mu$m, whereupon different behavior and much worse performance than the 2–4-$\mu$m ridge lasers were exhibited. The actual postprocessing thickness of the narrowest ridges turned out to be somewhat less than expected ($\sim 0.65$ $\mu$m), which might have increased optical losses and/or pushed the mode down into the cladding, contributing to the observed behavior.

Fig. 4 summarizes the results of $L-I$ measurement for LCI#1 lasers, showing the temperature dependence of the laser threshold and $L-I$ slope efficiency (above and below threshold), for lasers with ridge width $d$ varying from 2–4 $\mu$m. There are three distinct temperature ranges where the lasers exhibit different behavior.

Below a characteristic temperature $T_1 \sim 100$ K, LCI laser behavior differs significantly from the usual characteristics of vertical injection lasers. As temperature decreases, the threshold of the narrower lasers drops significantly, while that of the 4-$\mu$m lasers saturates. The observed temperature dependence of threshold thus varies strongly with ridge width and may even change sign, with decreasing $T$ increasing $J_{\text{th}}$ for wider lasers, but decreasing it for narrow-ridge lasers; as a result, the threshold currents of 2 and 4 $\mu$m lasers differ by more than an order of magnitude at $T < 50$ K. The 3 $\mu$m ridge laser in this temperature range exhibited lateral mode-switching, as described in the following section, with the first-order mode appearing before the fundamental mode. Their respective thresholds are shown in the Fig. 4 by up- and down-pointed triangles. These behaviors indicate first that the spatial asymmetry of the carrier and gain distributions across the active region indeed exist as predicted in earlier publications from our group [1], [13], and that it becomes more significant at low temperatures; the degree of overlap of the lateral waveguide modes with the gain profile becomes the governing factor for $T < 100$ K.

As temperature rises and approaches $T \sim 100$ K, the behavior difference between wide- and narrow-ridge devices diminishes, and for $T > 100$ K all the lasers behaved similarly, with threshold current depending slightly on ridge width and rising exponentially with characteristic temperature $T_0 \sim 55$ K. Also, the temperature dependence of the above-threshold
slope efficiency changes when temperature exceeds 100 K: at lower temperatures it is almost temperature-independent, but starts decreasing at approximately the same rate as increases in threshold current at $T_0 > 100$ K.

However, while the rate of increase in threshold current is about the same up to the highest lasing temperatures, the deterioration of slope efficiency abruptly increases at $T_2 \sim 200$ K, and quickly leads to vanishing of any threshold behavior (Fig. 2). It is thus the deterioration of the external quantum efficiency, not rising threshold, that prevents lasing at temperatures above 100 K for the LCI#1 lasers.

Fig. 5 shows similar dependencies for a 2-$\mu$m-wide LCI#2 laser of 300-$\mu$m length. In this case, as with the 2 $\mu$m laser from LCI#1 shown in Fig. 4, increasing temperature first leads to a strong increase in threshold current, which slows somewhat above 100 K and continues at about the same rate (with $T_0 \sim 56$ K) till the highest measured temperatures. The main difference between this laser and a similar laser from LCI#1, as seen by comparing Figs. 4 and 5, is the increase of the characteristic temperature $T_1$, above which laser efficiency starts to deteriorate, from 100 K to $\sim 200$ K. For LCI#2 lasers, no analog of a $T_2$ transition (onset of an abrupt lasing efficiency fall) was observed.

B. Far Field

The above results are consistent with the prediction of a lateral nonuniformity of carrier concentration, and hence gain, across active regions whose width is comparable or bigger than the ambipolar diffusion length. In GaAs-based structures the much higher mobility of electrons leads in this case to carrier pile-up at the p-i junction and asymmetrical gain distribution [13]. Intuitively, this gain asymmetry can be understood as follows: the width of the gain area is controlled by the ambipolar diffusion length $L_D$, which in the case of large mobility disparity is approximately equal to the hole diffusion length $L_D \sim (D_h\tau)^{1/2} \sim (\mu_h\tau kT)^{1/2}$. To better understand the deterioration of laser behavior with increasing temperature, we investigated the ridge-dependence of below-threshold slope efficiency, which is a measure of the efficiency of injection and radiative recombination. Room-temperature results for the LCI#1 lasers are shown in Fig. 6, where different symbols refer to samples from different bars. It shows that the injection efficiency quickly deteriorates with decreasing ridge width below 2–3 $\mu$m. This deterioration implies that a decreasing portion of injected carriers is converted into light, with the rest recombining nonradiatively and contributing to leakage current. This leakage is most likely caused by the escape of electrons from the active region into the p-injector, which is an important source of carrier leakage in VCI lasers as well [17], [18]; another probable mechanism is nonradiative recombination of carriers near the p-i junction, caused by the implantation-induced defects. Leakage caused by the former mechanism decreases as $d$ exceeds the ambipolar diffusion length $L_D$ of carriers in the active region. Fitting the data to an exponential dependence yields an estimate of $L_D \sim 1.2$ $\mu$m for our lasers.

The strong deterioration of injection efficiency at small $d$ shows that electron leakage is very profound in our lasers, pointing to insignificant implantation-induced intermixing of QW’s in the p-injector, and hence an insufficient lateral barrier for electrons at the p-injector boundary.
where $\mu$, $D$, and $\tau$ are the hole mobility, diffusion coefficient, and lifetime, respectively. For temperatures above 100 K, mobility usually increases superlinearly with inverse temperature; if we can neglect the temperature dependence of the carrier lifetime at threshold, the ambipolar diffusion length and hence the carrier uniformity should decrease with increasing temperatures, leading to greater gain asymmetry and thus smaller modal gain. At cryogenic temperatures, however, carrier mobility typically saturates or decreases again, such that decreasing temperature in this region should lower ambipolar diffusion length and thus make gain more nonuniform. Investigating the far-field emission of the lasers at different temperatures can assess such nonuniformity. We have performed such measurements and found that the far-field patterns of all tested devices demonstrate various degrees of nonuniformity, whose characteristics indeed differ according to temperature and ridge width, and may become quite complicated.

At low temperatures ($<90$ K for LCI#1 lasers, and $<150$ K for LCI#2 lasers), narrow-ridge lasers ($d = 2$ and 3 $\mu$m) exhibited mode switching, accompanied by kinks in their $L-I$ characteristics. Fig. 7 presents an example of an asymmetric LCI-laser mode switching associated changing far-field behavior; it shows the low-temperature $L-I$ characteristics of a LCI#2 laser of 2-$\mu$m width, which demonstrate a distinctive kink. This kink is caused by the modal gain difference associated with the asymmetric gain; as shown in the insets, the laser beam deflects to the n-contact side at small currents, but steers to the other side at higher currents. Note that increasing temperature delays the kink appearance, thus increasing the required optical power.

A symmetrical type of mode switching behavior, shown in Fig. 8, was observed at even lower temperatures ($T < 90$ K) in 3 $\mu$m lasers from LCI#1. As with the LCI#2 lasers, the $L-I$ characteristics showed a kink at progressively higher currents and optical powers as temperature increased; here, however, the kink corresponds to switching from the two-lobe first-order mode to the single-lobe fundamental mode as current increased. It is interesting that contrary to the usual situation, first-order mode lasing actually preceded that of the fundamental mode.

Abrupt mode-switching, either symmetrical or asymmetrical, was observed only for ridge widths of 3 $\mu$m or less, and only at low temperatures. At temperatures considerably higher than 100 K, or for 4 $\mu$m-ridge lasers at all temperatures, the $L-I$ characteristics showed no kinks, and no mode-switching or beam-steering was observed in the lasing regime; instead, the laser beam was always single-lobe and asymmetric, with a maximum at $\approx 5^\circ$–$15^\circ$ off the laser axis. Fig. 9 demonstrates such behavior for a 4-$\mu$m-wide LCI#1 LCI laser at 20 K, where the above-threshold far-field distribution is shown in comparison with the symmetrical spontaneous emission profile below threshold. This behavior is a sign of gain guiding, where the mode profile is governed to a large extent by the lateral gain profile. It explains why the lasing thresholds of 3- and 4-$\mu$m lasers do not greatly exceed that of the 2-$\mu$m-ridge laser at high temperatures: the lasing mode tends to adjust itself to the gain distribution, yielding a modal gain which is approximately independent of ridge width. This is illustrated in Fig. 9, which shows that the spectral position of the gain maximum at threshold (as measured by the laser wavelength), and hence the threshold carrier concentration, is very similar for 2, 3, and 4 $\mu$m lasers at high temperatures.
As temperature decreases, the lateral symmetry of the carrier distribution and gain profile increases, and the ability of the laser mode to adjust to the new profile becomes dependent on the ridge width. For the 2-μm-ridge lasers, mode-gain overlap improves for $T < 100$ K, yielding lower threshold current, higher spontaneous emission efficiency (Fig. 4), and lower gain-peak energy (Fig. 10).

For the 3-μm-ridge laser, the increased gain asymmetry at low temperatures yields a lower threshold for the first-order mode, with lasing switching to the fundamental mode at higher currents which produce a more uniform gain profile (Fig. 8). As shown in Fig. 4, the temperature dependence of threshold currents for the first-order and fundamental modes closely follows that of the 2 and 4 μm lasers, respectively. The near-coincidence of the mode threshold properties of the 3 μm ridge with those for 2 and 4 μm is even more significant if gain peak energies are considered (Fig. 10).

### C. Differential Resistance

Electrical characteristics, especially the bias dependence of the laser differential resistance $R_d = dV/dI$, are useful in investigating performance degradation mechanisms, and are often employed in characterizing VCI lasers (see, e.g., [19], [20]). Their importance is even greater for LCI lasers, as they carry information regarding the complicated roles of the various possible carrier transport paths associated with the lateral injection scheme.

To assess the electric properties of our lasers, we have measured their current versus voltage ($I-V$) characteristics in QW and pulsed regimes at different temperatures. Since numerical computations of differential resistance from measured $I-V$ data is prone to large error, we employed direct $R_d$ measurements using a modulation technique, whereby a small ac signal $\delta V_m$ at kilohertz frequencies was superimposed on a dc-bias voltage; the ratio of this voltage to the resulting ac current component $\delta I_m$ gives the differential resistance $R_d = \delta V_m/\delta I_m$.

$V = IR_s + V_f + V_a$  \hspace{1cm} (1)

where $R_s$ is the series resistance of the laser which includes contact and cladding resistance, $V_f$ is the voltage drop across the doping junctions, and $V_a$ is the voltage drop across the uniformly doped active region. In most modern VCI lasers the core layer is very thin, and the last term is negligible, so that the second term in (1) is responsible for any nonlinearities in $I-V$ characteristics. In bulk VCI lasers, carrier-pinning above threshold yields saturation of the voltage drop across the junctions, leading to an abrupt slope increase in the $I-V$ curve at threshold, or an abrupt decrease of differential resistance—i.e., a negative kink. In the ideal situation where pinning is absolute and there is no leakage current, the kink is given by [20]–[22]:

$$\Delta R_d = R_d(I_{th}^+) - R_d(I_{th}^-) = -m kT/eI$$  \hspace{1cm} (2)

where $R_d(I_{th})$ and $R_d(I_{th}^+)$ are the laser differential resistances just before and above threshold, respectively, $kT$ is the thermal energy, $e$ is the elementary charge, and $m$ is the diode nonideality factor. Below threshold the $I-V$ characteristics are that of a diode in series with a resistor, while above it they are linear with a slope determined by the series resistance $R_s$. 

Fig. 11 shows the differential resistance of our LCI lasers as a function of injection level for different substrate temperatures; it demonstrates quite unusual behavior, to some extent opposite to that of standard VCI lasers. First, all tested devices exhibited an abrupt increase in differential resistance at threshold (i.e., a positive differential resistance kink, as opposed to the negative one usually observed in VCI lasers [20]–[22]). Second, the temperature dependence of the kink’s magnitude $\Delta R_d$ is also contrary to usual VCI laser behavior: $\Delta R_d$ decreases with increasing temperature. And third, the differential resistance continues to drop above threshold, suggesting either incomplete carrier pinning or considerable leakage current.

The observed behavior can be qualitatively understood as follows. The total voltage applied to a laser can be presented as

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of the laser: \( R_d(I > I_{th}) = R_a \). However, leakage currents lead to super-linear \( I-V \) characteristics above threshold; the associated decreasing differential resistance is thus a signature of such a process.

However, the situation becomes more complicated for separate-confinement QW VCI lasers, where one should distinguish between carriers in the waveguide and barrier regions, often called three-dimensional (3-D) carriers; and carriers in the QW’s. While the latter interact directly with the light and thus are pinned above threshold, the former provides the required in-flow of carriers into the QW’s and is thus never pinned [23]; their concentration continues to grow above threshold as laser current increases. This growth translates into increased voltage across the active region, and hence a nonzero contribution of the core region to above-threshold differential resistance, which is then approximately given as [23]:

\[
R_d(I > I_{th}) = R_a + \frac{m k T}{e} \left( I + I_{th} \frac{\tau_{cap}}{\tau_{esc}} \right)
\]

where \( \tau_{cap} \) and \( \tau_{esc} \) are the effective carrier capture times to and from the QW’s, respectively. The above-threshold differential resistance of a VCI QW laser thus decreases with increasing current, which obscures the presence of leakage. If carrier escape from the QW’s is negligible, (3) yields \( R_d(I_{th}^+) = R_a - d(I_{th}^+) \), eliminating the differential resistance kink at threshold.

Lateral injection of carriers into a QW active region changes the situation, however, in two main ways. First, lateral injection can combine features of bulk and QW VCI lasers: in an LCI laser, carriers can be injected either directly into the QW’s, giving rise to a bulk-like behavior of the differential resistance; or they can first enter the barriers before capture to the QW’s, in which case one can expect differential resistance behavior similar to that of QW VCI lasers. Predominance of the direct injection mechanism is the likely situation in an ideal LCI laser, while the latter mechanism is significant in LCI lasers with current-guiding layers [5],[24]. In general, one can expect mixed injection, so that QW carrier-pinning would produce a differential resistance kink intermediate between (2) and (3).

Second, in the LCI case the injectors are much farther apart than in a standard vertical laser, and the active region resistance \( R_a \) is no longer negligible. Nonzero \( R_a \) gives rise to an additional voltage drop across the active region \( V_a = R_a I \); since \( R_a \) depends on the carrier concentration in the active region, carrier-pinning would lead to a change in slope of the \( I-V \) curve at threshold, and an additional contribution—positive in this case—to the differential resistance kink:

\[
R_d^a = \frac{d}{dI} (R_a I) = R_a + \frac{dR_a}{dN} \frac{dN}{dI}.
\]

Since \( R_a \) decreases with increasing carrier concentration, the second term in (4) describes a negative contribution to the differential resistance of a laser; carrier-pinning above threshold would eliminate this term, yielding a positive kink at threshold, as we observed experimentally. The kink magnitude can be estimated by assuming a certain dependence between QW carrier concentration and laser current; at high injection levels this can in many cases be approximated by a power law:

\[
I = I_s \left( \frac{N}{N_{th}} \right)^p.
\]

Here, \( p = 1 \) corresponds to the case where all current is associated with nonradiative recombination in the active region, and \( p = 2 \) for predominantly radiative recombination.

In the case of complete carrier-pinning above threshold, (5) produces a positive differential resistance kink:

\[
\Delta R_d = \frac{N}{m} \frac{dR_a}{dN} = \frac{R_a}{m} = \frac{1}{m} \frac{d}{dw} \frac{1}{eN_0 \mu h}
\]

with threshold carrier concentration \( N_{th} \), ridge width \( d \), laser length \( l \), total QW thickness \( w \), and carrier mobility \( \mu = \mu_p + \mu_e \). An order-of-magnitude estimate at room temperature gives a kink amplitude of \( \Delta R_d \sim R_a \sim 1 \Omega \), using typical values of the relevant parameters: \( N_{th} \sim 3 \times 10^{18} \text{ cm}^{-3} \), \( \mu \sim 3000 \text{ V cm}^{-2} \text{ A}^{-1} \), \( d = 1 \mu m \), \( l = 300 \mu m \), \( w = 300 \AA \) (three 100-Å wells, LCI#2 laser). It is not immediately clear, however, what kind of \( \Delta R_d \) behavior one should expect as the temperature decreases: although the mobility \( \mu \) increases with decreasing temperature, the threshold carrier concentration decreases, and the combined result depends on their respective rates of change.

According to our measurements (Fig. 11), \( \Delta R_d \) stays approximately constant at low temperatures and begins vanishing quickly above \(~80-100 \text{ K} \), disappearing completely at \( T \sim 180 \text{ K} \); this may signify either a change in the temperature dependence of mobility, or, more likely, in that of threshold carrier concentration, due for example to increasing nonuniformity of gain distribution.

Another possible mechanism for the positive differential resistance kink at threshold is current leakage into the p-injector [19]. Indeed, considerable electron escape into the p-doped region can lead to a significant decrease in the p-injector resistance. Since this escape is proportional to the carrier concentration \( N_0 \) at the p-i junction, its contribution to the differential resistance is negative below threshold, and disappears above threshold where \( N_0 \) is pinned. Similarly to [19], the p-injector contribution to the differential resistance below threshold can be estimated as:

\[
R_d^p = -\frac{1}{m} \frac{\mu_e}{\mu_h} \frac{\sigma N_0/\sigma_0}{1 + \sigma N_0/\sigma_0},
\]

where we assumed that the minority carrier diffusion length \( \mu_d^p \) in the p-injector is much smaller than the current path length there; \( \sigma_0 \) is the equilibrium p-injector conductivity; and \( \sigma = e(\mu_e^p + \mu_h^p) \), where \( \mu_e^p \) and \( \mu_h^p \) are the electron and hole mobilities in the p-injector region. If the active region carrier concentration is completely pinned above threshold, the differential resistance increases at threshold by the amount given by (7). Its temperature dependence, however, is not obvious either, and depends on a combination of mechanisms which govern the temperature dependencies in the p+ region of electron and hole mobility, carrier lifetime, carrier concentration, and so on. If the excessive conductivity of the p-injector
is small compared to that at equilibrium, the contribution of (7) is also small and proportional to the carrier concentration in the active region; its dependence on \(N_{th}\) is thus opposite to what we expect from the active region contribution (6). Note however that this contribution is proportional to \((i_{th}^2)^{-3/2}\), and thus may increase at very low temperatures when the onset of acceptor-band conductance leads to a significant drop in majority carrier mobility in the \(p^+\) region. In this case, though, the excess conductivity \(\sigma_0\) can become greater than the equilibrium conductivity \(\sigma_0^e\), making the differential resistance of the \(p^+\)-injector (7) independent of carrier concentration in the active region.

However, it is likely that (7) overestimates the injector contribution to the differential resistance kink at threshold, as it fails to account for the considerable voltage drop in the \(p^+\) injector near the active region. This voltage drop occurs in all lasers [17], [18] but can be especially severe in LCI lasers, due to their intrinsically higher current density operation (small QW cross section); e.g., assuming that all current enters the active region through the QW’s, a threshold current of 10 mA would correspond to a current density of 100 kA/cm\(^2\), for a 330-\(\mu\)m laser with three 100-Å QW’s. As a result, electron escape from the active region into the \(p^+\)-injector is not clamped above threshold even if the active region carrier concentration is, but is instead controlled by current and continues to increase with increased bias. This current-dependent leakage leads simultaneously to at least partial elimination of the threshold kink associated with the \(p^+\)-injector, and to continued reduction of the differential resistance above threshold, as is clearly visible in Fig. 11.

There is also another reason for the nonclamping of differential resistance above threshold. In LCI geometry, barrier layers can provide an additional carrier path parallel to the active QW’s, and together with the \(p^+\) and \(n^+\) injectors effectively constitute a diode connected in parallel to the laser diode/QW’s. The turn-on voltage of this shunting diode is higher than that of the laser diode due to the higher bandgap of the barrier layers. As bias increases, however, the considerable current and resistance of the active layer leads to an increasing voltage drop across the active region and a gradual opening of the barrier shunting diode. This yields a diode-like \(R_d(I)\) dependence above threshold (see Fig. 11), and increasing leakage through the high-bandgap barrier layers. Assuming that the differential resistance step of up to \(\sim 4\ \Omega\) in Fig. 11 can be taken as an estimate of the active region resistance, a 50-mA current adds \(\sim 200\ \text{mV}\) of increased voltage across the barrier-layer diode. Although more experiments are required to separate the two leakage mechanisms discussed above, the latter effect may be responsible for the catastrophic decrease in quantum efficiency of the LCI#1 lasers at \(\sim 200\ \text{K}\), where their thresholds reach about 50 mA.

IV. CONCLUSION

We fabricated for the first time two sets of OEIC-compatible ion-implanted LCI lasers with differing active regions and ridge width. The laser structures with higher barriers better confinement factor and active region \(p\)-doping demonstrated significantly better performance and lasing at room temperature.

The optimum ridge width was found to be \(\sim 0.8 - 1.5\ \mu\text{m}\), with threshold current \(J_{th}\) increasing for both wider and narrower devices; however, optimum ridge width is likely dependent on the degree of QW intermixing, and hence bandgap widening, in the contact regions.

Behavior of the fabricated LCI lasers with implanted contacts differs from that of vertical injection devices in several major aspects, including a positive kink at threshold in \(dV/dI\) versus \(I\) (Fig. 11) associated with the finite resistance of the active region (as opposed to the negative kink for VCI lasers); first-order mode lasing preceding fundamental mode lasing for wider ridges (Fig. 8); rising quantum efficiency and decreasing threshold as temperature increases for \(T < 40 - 60\ \text{K}\) (Fig. 4); and fast efficiency rolloff for \(T > 200\ \text{K}\). Moreover, behavior varied qualitatively in different temperature ranges (Figs. 4, 5): the probable dominant factor at low \(T < 100\ \text{K}\) is the temperature-dependence of diffusion coefficient and mobility, and at high \(T > 200\ \text{K}\) is electron escape (leakage) from the active region.

From the below-threshold \(L-I\) slope as a function of ridge width \(d\), we found that increased \(J_{th}\) for narrower devices is caused by decreasing injection efficiency and increasing electron escape to the \(p\)-contact region as \(d\) becomes smaller than the ambipolar diffusion length \((\sim 1.2\ \mu\text{m} at 273\ \text{K}) for our structures). This leakage was found to be the main cause of quantum efficiency deterioration at high temperatures for both sets of lasers, with much more severe effects for the LCI#1 lasers (Figs. 2 and 4). However, leakage was greatly reduced for the LCI#2 lasers by employing a wide \(p\)-doped active region with higher barriers, yielding lasing at temperatures above 300 K. In the pulsed regime, 300-\(\mu\)m-long LCI#2 lasers of ridge-width 1.6 \(\mu\text{m}\) had a 45-mA threshold at room temperature. The lasers from both sets suffered from a large contact resistance, which impeded CW lasing at room temperature and must be optimized. At cryogenic temperatures, however, their characteristics (230 \(\mu\text{A} \\text{CW threshold and } \sim 0.3\ \text{W/A facet slope efficiency for the above-mentioned LCI#2 lasers}) are comparable to those of the best ridge-waveguide VCI lasers of similar dimensions at the same temperature.

Analysis of threshold current and emission efficiency in both laser and LED regimes, together with far-field and electrical characteristics, indicate a strong temperature-dependent influence of lateral carrier nonuniformity on laser characteristics, with continuing changes in the carrier profile above threshold (local carrier nonpinning effect). These phenomena, together with high-current density and insufficient lateral carrier confinement, explain the increased carrier leakage found in the LCI lasers, but also highlight directions for future improvements. Analysis and comparison with theoretical results show that a short and thick active region, high MQW intermixing in the contact regions (or buried LCI structures), and possibly heavier doping of the \(p^+\) lateral cladding layers are required, in order to overcome the observed negative effects and achieve an LCI laser competitive in performance with VCI counterparts.
We also found that the chosen ion-implantation approaches, whereby a p-injector was created with high-dose implantation of Be with and without P followed by rapid thermal annealing, did not give any significant QW intermixing for any attempted combination of implantation dose and annealing regime. This was inferred from laser behavior, and was also proven directly by low-temperature PL measurements. It was suggested in a recent publication that high concentrations of acceptors such as Be [25] can actually block implantation-induced intermixing.

Development of different implantation techniques which produce considerable intermixing of the QW’s in the injector regions, especially in the p-injector, together with careful adjustment of the contact recipes and considerable improvements in contact resistance, are currently under way and should yield OEIC-compatible LCI lasers with competitive performance.

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