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REDUCED POWER CONSUMPTION IN GaAs-BASED BIPOLAR CASCADE LASERS


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**TITLE AND SUBTITLE**
REDUCED POWER CONSUMPTION IN GaAs-BASED BIPOLAR CASCADE LASERS

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**ABSTRACT**
A systematic study of GaAs tunnel junctions for use in bipolar cascade laser diodes was performed. We investigate the current voltage characteristics of individual degenerately doped n+ and p+ regions grown by MBE and then place the most promising designs within the individual laser substructures. This has resulted in a 1 V reduction in operating voltage, as verified by comparing the lasing characteristics of several edge-emitting laser devices.
Reduced Power Consumption in GaAs-Based Bipolar Cascade Lasers


A systematic study of GaAs tunnel junctions for use in bipolar cascade laser diodes was performed. We investigate the current voltage characteristics of individual degenerately doped $n^+$ and $p^+$ regions grown by MBE and then place the most promising designs within the individual laser substructures. This resulted in a 1 V reduction in operating voltage, as verified by comparing the lasing characteristics of several edge-emitting laser devices.

*Introduction:* Bipolar cascade lasers (BCLs) show excellent potential for producing gain in radio frequency (RF) photonic links[1], improving the efficiency of high-power diode lasers[2], and realizing multiple-color laser devices [3]. High-speed BCLs can be used as the direct-drive optical carrier for an RF photonic link system. The benefits of a BCL over a standard high-speed diode laser include an increased device quantum efficiency, which can be greater than unity, and improved RF impedance matching, since the BCLs can be closely matched to the load impedance by engineering the number of epitaxially grown active region stacks.

A BCL consists of stacked quantum well active regions separated by reverse-biased tunnel junctions (TJ). BCLs offer many design tradeoffs, since they can be multiple-cavity or single-cavity devices, and they can be edge- or surface-emitting structures. For a multiple-cavity device each active region exists within its own optical cavity. In a single-cavity device all of the active regions and tunnel junctions are in a single optical cavity. In this article we present the results of our studies on the development of high quality GaAs tunnel junctions grown and incorporated
into multiple-cavity BCLs. We present improved lasing performance in multiple-cavity edge-emitting BCLs with multiple-color emission.

Tunnel Junctions: GaAs tunnel junctions are difficult to develop and very little technical detail has been reported in the literature, except from tandem solar cell research [4, 5]. In GaAs-based diodes and BCLs, a major difficulty is achieving high electron concentrations in the n-doped region. When silicon is used as the n-dopant, it becomes amphoteric as the doping concentration increases beyond 5x10^{18} \text{cm}^{-3}. To evaluate tunnel junction performance, several designs were grown in a Varian Gen II MBE system. In all of these structures a 1000 Å GaAs:Si (5x10^{18} \text{cm}^{-3}) buffer layer was grown on an n-doped GaAs substrate held at 600° C. After the buffer layer was completed the substrate temperature was lowered to 510° C to provide growth conditions for In_{0.20}Ga_{0.80}As quantum wells. The n-layer of the tunnel junction was formed by growing ten, 10 Å GaAs:Si (5x10^{18} \text{cm}^{-3}) layers separated by nine, 25 second (Si sheet concentration of 5.5x10^{12} \text{cm}^{2}) or 40 second (Si sheet concentration of 8.8x10^{12} \text{cm}^{2}) silicon δ-doped “layers,” which are simply growth delays while the silicon and arsenic shutters remain open and the gallium shutter is closed. The effective ionized doping concentration, \( n_{\text{eff}} \), was measured using Hall and electrochemical capacitance-voltage techniques. A 600 Å GaAs:C (5x10^{18} or 8x10^{18} \text{cm}^{-3}) p-layer of the tunnel junction was then grown. Table 1 summarizes the tunnel junction thickness and concentration values used in this study. The tunnel junction devices were processed into squares of varying dimensions with an evaporated Ti:Pt: Au metal contact and annealed at 410° C for 15 seconds. The entire backside was evaporation coated with a standard Ni:Ge: Au:Ni: Au ohmic metal and, again, alloyed at 410° C for 15 seconds.
Figure 1 shows the room-temperature I-V characteristics of four 200 x 200 μm$^2$ tunnel junction devices. The carbon doping concentration clearly influences the onset of negative differential resistance (NDR) in the tunnel junction device. These results also demonstrate the importance of silicon δ-doping parameters on the peak-to-valley characteristics of NDR; silicon δ-doping at too high a level results in the silicon becoming an amphoteric dopant. The results from sample TJ #2 clearly demonstrate the desired characteristics of a steep reverse-biased slope and strong evidence of NDR, required for effective BCL operation.

*Bipolar Cascade Lasers:* The BCLs were grown in the same MBE system. The BCL designs consist of two epitaxially stacked lasers: each with 1 μm Al$_{0.6}$Ga$_{0.4}$As digitally alloyed n- and p-cladding layers, silicon- and carbon-doped respectively to 4x10$^{18}$ cm$^{-3}$, 2000 Å undoped Al$_{0.2}$Ga$_{0.8}$As ternary electrical confinement layers, 100 Å GaAs barriers, and either three 80 Å In$_{0.2}$Ga$_{0.8}$As quantum wells for emission at 980 nm or three 50 Å In$_{0.2}$Ga$_{0.8}$As quantum wells for emission at 950 nm. These lasers were separated by a reverse-biased tunnel junction consisting of a 100 Å silicon δ-doped layer, described above, and either a 600 Å or 100 Å carbon-doped layer doped at 5x10$^{19}$ cm$^{-3}$ or 8x10$^{19}$ cm$^{-3}$. The 600 Å carbon-doped layer was used to replicate the tunnel junction device development and the 100 Å carbon-doped layer thickness was used to evaluate the effect of thickness reduction on laser device properties. The BCLs were fabricated into gain-guided lasers with varying device widths and lengths. Room-temperature pulsed and CW L-I characterization and spectral analysis were performed on all growth structures.

Figure 2 shows a comparison of the L-I and V-I characteristics for the three BCL devices studied and Table 2 provides a summary of the BCL layer characteristics. The stripe geometry was 20
μm wide by 500 μm long for all of the devices. The first room-temperature CW operating BCL (BCL #1) had a tunnel junction with a 600 Å carbon p-doped layer at 5x10^{19} \text{ cm}^{-3}. The bottom laser lased first at ~960 nm with a threshold current of 144 mA. The second laser threshold occurs at 247 mA with a lasing wavelength ~990 nm. The overall BCL voltage is more than twice the normal operating voltage for a standard InGaAs triple quantum well laser diode indicating additional losses due to the tunnel junction. The next two multiple-cavity, multiple-color BCLs (BCL #2 and BCL #3) were grown to provide a systematic study of the effect of changing the p-doped layer of the tunnel junction to either a 600 Å or 100 Å C-doped layer doped at 8x10^{19} \text{ cm}^{-3}. This p-doping concentration, in both BCL #2 and BCL #3, had the best performing tunnel junction characteristics, as shown in Figure 1. As Figure 2 shows there is a dramatic reduction in operating voltage for both of these devices compared to BCL #1. Increasing the p-doping concentration significantly improves device operating voltage performance. Reducing the p-doped thickness of the tunnel junction has little or no effect on the voltage performance with minimal effect on threshold current. The use of this layer is important for making single-cavity BCLs because we desire the smallest possible tunnel junction layer thickness.

Summary: We have successfully demonstrated multiple-cavity BCLs. We have significantly improved the device performance by increasing the p-doping concentration in the tunnel junction from 5x10^{19} \text{ cm}^{-3} to 8x10^{19} \text{ cm}^{-3}. Extracting device differential quantum efficiency will require single-color devices. Development of single-cavity single-color BCLs will be required for single-mode operation frequency modulation and relative intensity noise (RIN) experiments.
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References


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Table 1: Details of tunnel junction layer parameters. All $p$-doped layers are 600 Å, the total $n$-layer thickness is 100 Å with ten 10 Å layers doped at 5x$10^{18}$ cm$^{-3}$ and 9 δ-doping interrupts resulting in the following effective $n$-doping concentrations, $n_{\text{eff}}$, as measured using Hall and electro-chemical C-V techniques.

<table>
<thead>
<tr>
<th>TJ #</th>
<th>$p$-doping (10$^{19}$ cm$^{-3}$)</th>
<th>$n_{\text{eff}}$-doping (10$^{19}$ cm$^{-3}$)</th>
<th>Si δ-doping (seconds)</th>
<th>Sheet Concentration (10$^{12}$ cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.8</td>
<td>40</td>
<td>8.8</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>2.0</td>
<td>25</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.8</td>
<td>40</td>
<td>8.8</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2.0</td>
<td>25</td>
<td>5.5</td>
</tr>
</tbody>
</table>
Table 2: Details of bipolar cascade laser parameters. All other layer parameters are the same for each sample grown.

<table>
<thead>
<tr>
<th>BCL #</th>
<th>p-doping $(10^{19} \text{ cm}^{-3})$</th>
<th>p-thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 1: Room-temperature current versus voltage characterization for 200 μm by 200 μm tunnel junction devices. The dashed line is TJ #1, the solid line is TJ #2, the dotted line is TJ #3, and the dot-dashed line is TJ #4.
Figure 2: Room-temperature comparison of L-I and V-I operating characteristics for three BCL devices studied. Device dimensions are all 20 μm wide by 500 μm long. The solid line is for BCL #1, the dashed line is for BCL #2, and the dotted line is for BCL #3. The inset shows the normalized lasing spectrum at a bias current of 300 mA.