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Wavelength switching transition in quantum dot lasers

Hsing-Yeh Wang,[a] Hsu-Chieh Cheng, Sheng-Di Lin, and Chien-Ping Lee
Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan 30043, Republic of China

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Control and the selection of the ground state emission and/or the excited state emission of an InAs quantum dot laser have been demonstrated. By controlling the currents injected into each section of a two-section cavity, switching between the ground state emission and the excited state emission with a separation of 100 nm was achieved. With a constant total current, either ground state lasing (~1.3 μm), excited state lasing (~1.2 μm), or dual state lasing can be obtained simply by adjusting the current ratio between the two sections. © *2007 American Institute of Physics*.

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InAs self-assembled quantum dots (QDs) have been extensively used as active region in semiconductor lasers.[1–3] These QDs generally exhibit two distinct peaks in photoluminescence spectra[4,5] corresponding to the ground and the excited state transitions in the dots. In laser operations, either one can be the dominant lasing mode depending on the cavity length, the dot density, the driving current, and other structural parameters. Once the laser fabrication is completed, the control of the lasing mode becomes difficult. Whether one can controllably switch the lasing mode from the ground state to the excited state or vice versa is an important and an interesting subject. Zhou *et al.* have previously studied the switching behavior of QD lasers using a coupled-cavity structure, where one laser section was accompanied by a saturable absorber region.[6] By adjusting the voltage of the absorbing region, a 15 nm change in wavelength or ~20 meV change in energy was obtained. This change, however, is unlikely due to the switching between the ground state and the excited state transitions normally observed in photo luminescence (PL) spectrum because the energy separation was too small compared to the separation of the two PL emission peaks. More recently, Markus *et al.* reported a clear ground/excited state switching, again using a gain section and an absorber section.[7] A 65 meV switching was obtained. However, in these approaches, an absorber section is always used as the controlling device for mode switching while the gain section is used for providing the laser gain.

In this study, we demonstrate a clear ground to excited state switching (around 100 nm or 75 meV) using a two-section quantum dot laser. Both sections were forward biased and were used as either the gain or the absorbing regions. By adjusting the amount of currents going into each section, switching between the ground state emission, ~1.3 μm, and the excited state emission, ~1.2 μm, was obtained. The energy separation between these two switchable states was 75 meV.

The QD lasers were grown on (100)-n^+GaAs substrates using molecular beam epitaxy. The epitaxial layers consist of, starting from the bottom, a 1.2 μm thick n-type $Al_{0.4}Ga_{0.6}As$ cladding layer with 3×10^{17} cm^{-3} Si doping, a 0.4 μm thick undoped GaAs waveguide layer, a 1.2 μm thick p-type $Al_{0.4}Ga_{0.6}As$ upper cladding layer with 3×10^{17} cm^{-3} Be doping, and finally a 200 nm thick p^+-GaAs contact layer. The active region consists of six InAs QD layers, which reside in the middle of the waveguide layer. Each QD layer is capped by a 6 nm $In_{0.15}Ga_{0.85}As$ layer and a 40 nm GaAs barrier layer is inserted between the QD layers. Conventional ridge waveguide structure was used for laser fabrication. The laser cavity, however, was electrically divided into two sections separated by a 5 μm gap. The top contact layer and the upper p-type cladding layer in the gap were removed by chemical etching to ensure good electrical isolation between the two sections. The structure of the device is schematically shown in Fig. 1.

The fabricated laser waveguide had a width of 20 μm. The lengths of the two sections were 300 and 850 μm. By injecting different amounts of currents in the two sections, we were able to control the lasing mode. Either section can be used as the gain region or the absorbing region. In other words, either section can be used to control the mode switching. Pure ground state lasing, excited state lasing, or both state lasing are achievable by merely adjusting the current ratio of the two sections.

Figure 2(a) shows the lasing characteristics as functions of the currents injected into the two sections, the horizontal axis being the current injected into the shorter section and the vertical axis being the current injected into the longer section. The emission wavelength of the ground state transition is 1294 nm while that for the excited state transition is 1200 nm. Different lasing modes take place in different regions in this two-dimensional plot. The boundary of the data in each region indicates the threshold condition. Clearly two boundaries can be identified, one for the ground state lasing and the other for the excited state lasing. The allowed lasing region is where the currents are higher than the boundary. The overlap area of the two allowed regions is where the dual state lasing takes place. We notice that the threshold

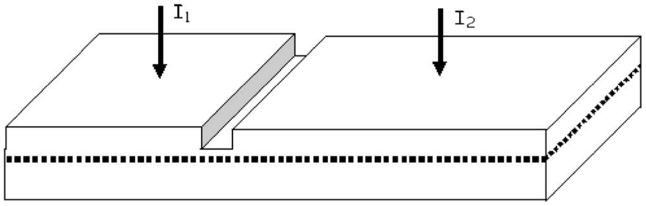

FIG. 1. Schematic of the two-section laser structure

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[a] Electronic mail: hywang.ee89g@nctu.edu.tw

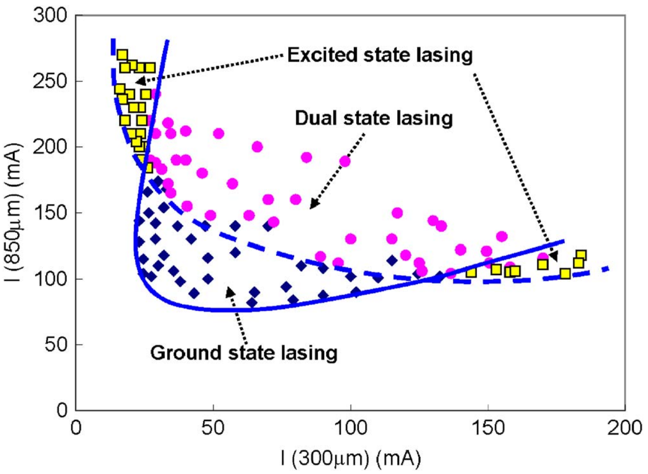

FIG. 2. (Color online) Lasing mode distribution vs input currents to the two sections of the laser cavity.

boundaries bend inwards at high currents, especially for the ground state threshold curve. In other words, if we increase the current injected into one of the sections, the current going to the other section needs to be increased also in order to reach the threshold condition. This is in contrary to what one would expect because the optical gain in each section should increase with the injection current. However, when we map the threshold condition shown in Fig. 2, the currents used are relatively high compared to what one would normally use to operate a laser. The effect of heating causes the gain to drop because the Fermi distribution is a function of temperature. So higher currents are needed in order to reach the threshold. This phenomenon is particularly obvious for the ground state lasing. This is because the gain at a lower lasing energy is affected more by the Fermi function, causing the saturated gain to drop.

This current dependent lasing mode distribution can be understood as follows. The gain due to ground state transition is limited (by the dot density) and saturates at high currents. If the cavity loss is low, the ground state will lase first. But if the current injected to one of the section is not enough or even below transparency, the gain required from the other section has to be increased in order for the total loop gain to reach the threshold condition. This required gain may go beyond the saturation value of the ground state. So in this case the ground state cannot lase. The only state that can lase is the excited state, which, because of a higher density of states, can provide a higher gain as long as one of the section has a high enough current. This is why that the sole excited state lasing occurs when one section has a very high current while the other one has a low current. The dual state lasing happens when currents to both sections are high and it happens in a very wide range. The origin of dual state lasing has been discussed previously and has been attributed to partial clamping of the carriers in the ground state after threshold.[8–11]

Based on the result shown in Fig. 2(a), one can clearly see that wavelength switching among various QD lasing modes is possible through the variation of currents applied to the separate sections. If we fix the total current and simply change the ratio of the currents applied to the two sections, it is possible that we can switch among ground state lasing, excited state lasing, and dual state lasing. Figure 3 shows the spectra at three different current ratios along the line with a constant total current of 225 mA. Three different lasing modes were obtained at three different current ratios. The amount of wavelength change is around 100 nm.

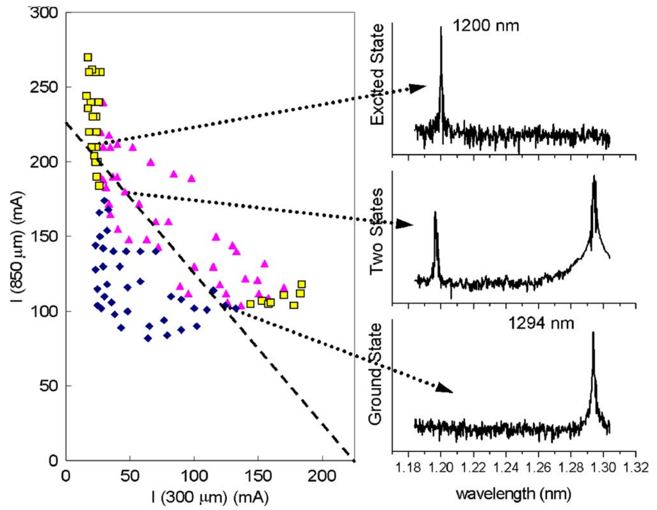

FIG. 3. (Color online) Lasing mode switching by adjusting the ratio of the currents injected into the two sections. The three spectra, corresponding to ground state, dual state, and excited lasing, were measured along a constant current line with a total current of 225 mA.

In conclusion, we demonstrated two-state switching, between the ground state ~1.3 μm and the excited state ~1.2 μm, of an InAs quantum dot laser using a two-section quantum dot laser. Mode switching was achieved by adjusting the gain of each section by the current injected into that section. With a constant total current, we were able to switch between 1.2 and 1.3 μm emissions simply by adjusting the current ratio applied to the two sections.

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