Lateral Carrier Injection with n-type Modulation-doped Quantum Wells in VCSELs

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We have demonstrated a novel Field-Induced Charge-Separation Laser (FICSL) in a Vertical-Cavity Surface-Emitting Laser (VCSEL) embodiment. In addition to the initial optical modulation results that have been presented [1], we here for the first time present details on the novel lateral charge injection structure as well as the advanced bandgap engineering involved in the gate structure. These features together permit high-speed light modulation with a nearly constant injection current. The result is an entirely new concept for high-speed directly-modulated semiconductor lasers.

In conventional diode VCSELs, carriers are typically injected into the quantum wells from the perpendicular direction (Fig. 3a-b). The common epitaxial design is a SCH (Separate Confinement Heterostructure) with p-type and n-type DBR mirrors on the opposite side of the active region. On the other hand, to realize direct modulation via a gate voltage, any highly doped intra-cavity contact layer above the quantum wells such as in Fig. 3b would pin the Fermi level, screening the driving force from the gate. Hence, carriers have to be injected laterally into the active region (Fig 3c). To allow only hole movement and isolate the electrons between the active channel and the off-state well, the first period of the n-DBR has to be band-gap engineered to form a quantum barrier (Fig. 4).

Lateral injection of carriers into quantum wells has been demonstrated on lateral current injection (LCI) lasers. However, the sheet resistance in LCI lasers is typically 2-3 times higher than a vertically-injected ridge laser with the same dimensions [2]. In a VCSEL structure, the comparatively small dimensions makes the sheet resistance even more detrimental, especially when there has to be a finite setback distance *d* between the current aperture edge and the metal ring contact to avoid absorption loss (Fig. 1). To enhance the conductivity of lateral injection, delta-doping can be applied to the quantum well barriers to provide free carriers.

Early research showed that modulation doping was promising for quantum well performance [3]. Furthermore, both n-type and p-type doped quantum wells have been incorporated into diode lasers and demonstrated the reduction of threshold current density [4, 5]. However, doping near the optical standing wave E^2 peaks has to be treated carefully since the increase in absorption loss and dopant scattering may compromise overall performance, rendering the delta-doping benefit marginal.

To examine lateral injection with two-dimensional electron gas (2DEG) and two-dimensional hole gas (2DHG), three $In_{0.2}Ga_{0.8}As/GaAs$ quantum well samples were grown by Molecular Beam Epitaxy with different delta-doping level in the barriers; silicon was used for n-doping, and carbon via a CBr_4 source was used for p-doping. The sheet charge density and the carrier mobility of these samples were acquired by room temperature Hall measurement, and the overall sheet conductivity was calculated (Fig. 5). It is clear that due to the large difference in mobility, the conductivity of 2DEG is more than one order of magnitude higher than a 2DHG with the same sheet charge density. Material gain of the modulation-doped quantum wells was characterized by fabricating broad area lasers. It was confirmed that both n-type and p-type modulation-doping reduced the transparency current density, while p-type doping also increased the differential gain, *dg/dJ* (Fig. 6).

Due to the large difference in conductivity, n-type modulation-doped quantum wells are chosen to form the active channels. FICSLs were fabricated and the measurement results are shown in Fig. 7. The required gate voltage swing was higher than expected, indicating that the fabricated FICSLs had very large resistance in the n-DBR, causing a large voltage drop. The large n-DBR resistance also limited the small-signal bandwidth to be around 11GHz [1]. The differential series resistance between injector and channel was measured to be 550Ω in a 5μm (aperture diameter) device.

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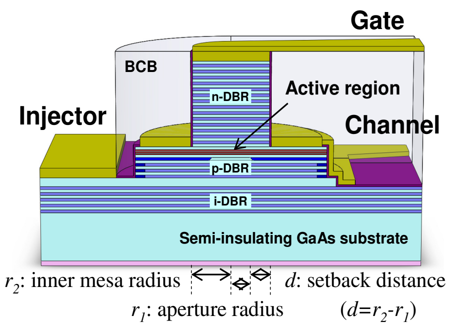

Fig. 1. Schematic of a FICSL. The injector-channel junction is DC biased, while the gate is the modulation terminal.

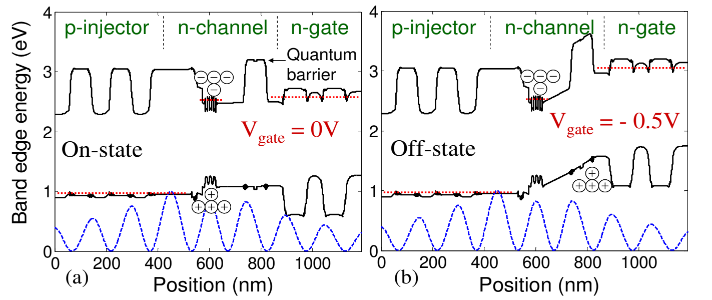

Fig. 2. Band diagrams of a FICSL (a) on-state: electrons and holes are aligned with a standing wave E^2 peak to provide gain. (b) off-state: a negative bias is applied to the gate, driving holes away from electrons and reducing output power.

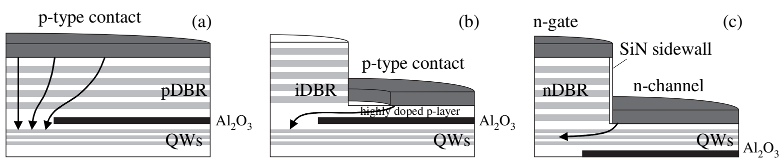

Fig. 3. Structural comparison of oxide-confined VCSELs: (a) top-contacted (b) intra-cavity contacted (c) laterally injected FICSL with top gate for modulation (this work). Arrows depict carrier injection flows. Oxide aperture layers are typically placed on the p-side due to the low spreading characteristics of holes compared to electrons.

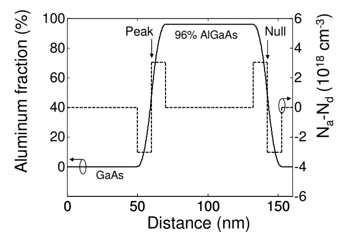

Fig. 4. Quantum barrier design to isolate electron transport.

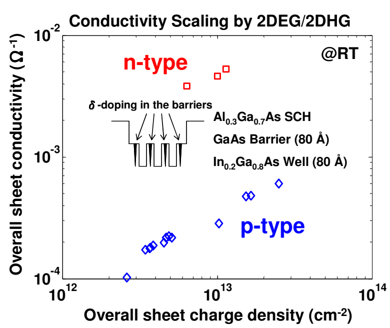

Fig. 5. Sheet charge conductivity of 2DEG and 2DHG in three modulation δ-doped quantum wells.

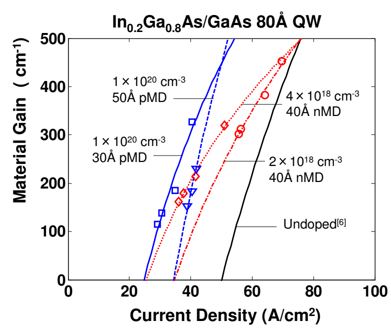

Fig. 6. Gain characteristics of modulation-doped QWs. Both n-doping and p-doping reduce transparency current density.

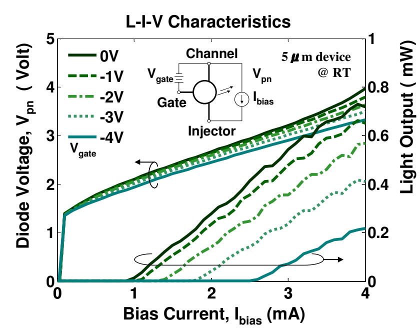

Fig. 7. DC performance of FICSL. Above threshold, negatively biasing the gate would reduce the light output given the same bias current to the injector-channel junction.

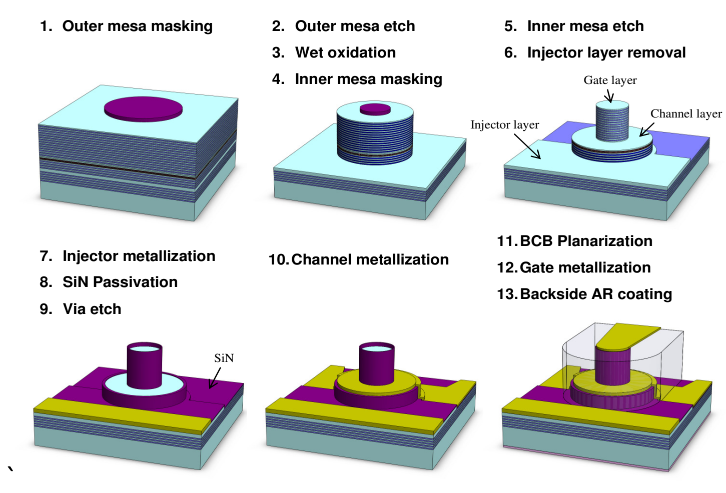

Fig. 8. Process flow for FICSLs. All steps are done with i-line lithography.

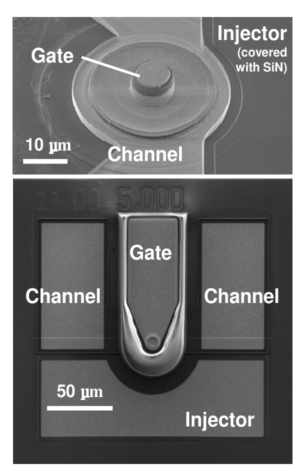

Fig. 9. SEM images of a fabricated FICSL before BCB planarization (upper) and after the completion of process (lower).