FIRST DEMONSTRATION OF MODULATION VIA FIELD-INDUCED CHARGE-SEPARATION IN VCSELS

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Abstract — Novel three-terminal field-induced charge-separation lasers (FICSLs) in VCSEL form were designed and fabricated. The new gain modulation mechanism of hole-electron separation was demonstrated for the first time by applying a variable gate voltage with a constant injection current to the active region.

I. Introduction

High-speed, high-efficiency diode VCSELs are the cornerstones for short-haul fiber links and free-space boar-to-board optical interconnects due to their small footprints, low power dissipation, low cost, and capability of being fabricated into 2D arrays. State-of-the-art diode VCSELs lasing at different wavelengths have been reported to demonstrate above 35 Gbit/s operation and above 20 GHz bandwidth [1-3]. However, the modulation bandwidth of conventional current-modulated diode lasers is limited by double-pole roll-off of the relaxation resonance response as well as carrier transport effects [4].

In this paper, we propose a novel three-terminal field-induced charge-separation laser (FICSL). Beginning with the basic structure of a dual-intracavity-contacted diode VCSEL, a third terminal (**gate**) is added to the top n-doped DBR mirror to apply a modulation field to the active region, while the top intracavity contact is directly connected to the quantum wells of the active-n (**channel**) region for electron injection. The bottom intracavity contacted p-layer is grown beneath the active region for hole injection. A cross-sectional schematic is shown in Fig. 1. A forward DC-bias is applied between the bottom-p (**injector**) and the active-n (**channel**).

The modulation mechanism is outlined in Fig. 2a. When no bias voltage is applied on the gate, electrons and holes overlap well and the modal gain is maximized. On the other hand, when a negative bias is applied on the gate, holes are pulled toward the gate while electrons are pushed away from the gate. Consequently, the overlap between two types of carriers decreases, causing a reduction in modal gain, an increase in threshold current, and a reduction in output power for a given DC bias current.

Modeling has illustrated that this sort of modulation of the photon rate equation, rather than the carrier rate equation, results in the addition of a zero in the numerator of the small-signal response, which compensates for the dual-pole roll-off in the denominator. Also, carrier transport effects are suppressed. The net result is a vast increase in the modulation bandwidth. Additional bandgap engineering is necessary to reduce the carrier lifetime when the carriers are separated in order to flatten the small signal response as illustrated by the band diagram in Fig. 2b. Fig. 3c compares the small-signal response of a conventional diode laser using experimentally verified parameters from ref. [1] with a FICSL that has the same parameters, but takes on the design of Fig. 1. From the modeling results, one can clearly see that FICSLs benefit from the additional zero ω_z in the modulation transfer function that is lower than the relaxation resonance frequency, ω_R. As a result, FICSLs have much higher 3dB cutoff frequency than conventional

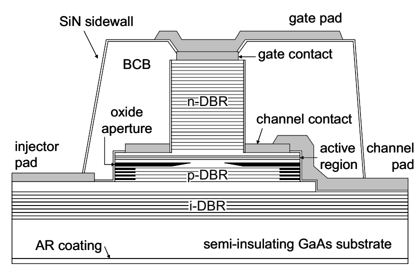

Fig. 1. Cross-sectional schematic of FICSL

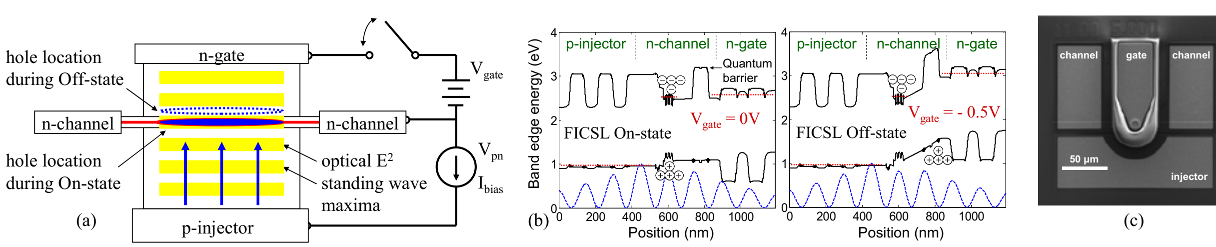

Fig. 2. (a) Operation mechanism of FICSLs showing separation of charges with bias voltage on the gate. (b) Band edge diagrams showing aligned (left figure) and separated (right figure) electron-hole pairs. (c) SEM top-view of a fabricated FICSL.

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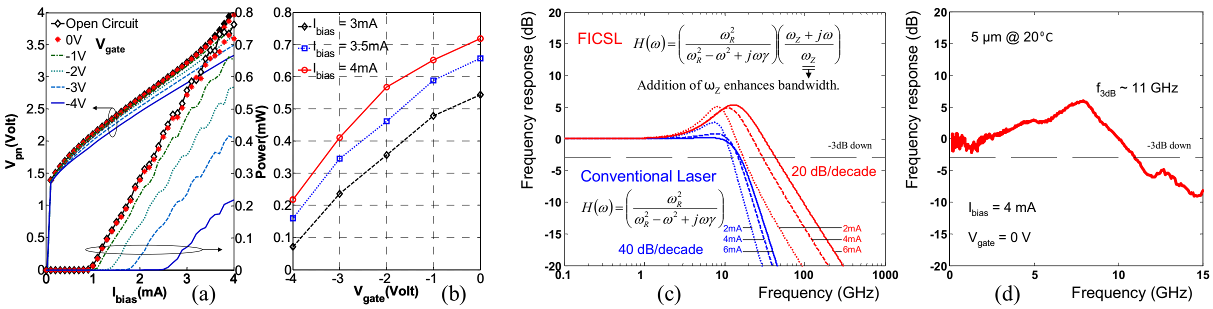

Fig. 3. (a) Room temperature CW L-I-V curves for 5μm device showing that L-I curves shift with V_{gate}. (b) L-V_{gate} curves at different I_{bias}. (c) Modeled small-signal response comparison of a conventional laser and a FICSL with same parameters and reduced carrier lifetime. Bias current I_{bias} was 2 mA, 4 mA and 6 mA. (d) Measured small-signal response for a 5 μm device.

diode lasers and slower roll-off at high frequencies (20 dB/decade vs. 40 dB/decade), making this novel field-induced charge-separation modulation extremely promising for future high-speed laser applications.

II. Device structure

The p-i-n-i-n base structure was grown on a semi-insulating GaAs (100) substrate by molecular beam epitaxy. The bottom emission design enables easy testing and flip-chip bonding to electronic ICs. The PN junction consists of a carbon-doped intracavity contact layer for p-injector, five period of p-type GaAs/AlGaAs DBR, a tapered oxide aperture layer, and three InGaAs/GaAs quantum wells with δ-doped Si in barriers as the active-n(channel) layer. The n-gate for voltage control consists of a bandgap engineered quantum barrier, Si-doped GaAs/AlGaAs DBRs and a highly-doped n-contact layer. The wafer was fabricated into double-mesa devices with high-frequency ground-source-ground (GSG) contact pads for on-wafer probing, as shown in Fig. 2c. Benzocyclobutene (BCB) was used to reduce parasitic capacitance. An anti-reflection coating was applied to reduce the reflection from the backside of the wafer.

III. Results

DC testing was done with the configuration shown by Fig. 2a. The experimental results for a 5 μm device are shown in Fig. 3a. When no bias voltage V_{gate} was applied, the FICSL demonstrated a threshold current around 1mA and output powers up to 0.8mW at an injection current I_{bias} of 4 mA. As we increased the negative bias V_{gate}, the threshold current increased while the differential quantum efficiency η_d and the output power decreased. When the bias current I_{bias} was fixed, the output power could be modulated by V_{gate}; as Fig. 3b demonstrated, with a bias current I_{bias} fixed at 3 mA, a -2 ± 2 V swing on V_{gate} provides a 0.3 ± 0.23 mW swing on the output. The voltage required for modulation is higher than expected due to a highly-resistive n-gate.

RF small-signal measurements were also performed to verify the modulation response. The results from a 5 μm device are shown in Fig. 3d. Due to the low output power available, performance above 15 GHz is hard to measure and the high-frequency roll-off is hard to be compared with the theoretical model. The highly-resistive n-gate also limited the RF performance and a 3dB cutoff frequency of 11 GHz was observed.

IV. Conclusion

We have demonstrated novel direct modulation mechanism via field-induced charge-separation in FICSLs that take on the form of VCSELs. By applying a field to separate the charges injected into the active region via intracavity contacts, we were able to directly modulate the gain, which promises to provide operation at higher-speeds than conventional current modulation. Experimental results verified the expected DC and RF characteristics. The highly-resistive n-gate increased the voltage required for direction modulation and decreased the RF bandwidth compared to the expected values.

V. References

[1] Y.-C. Chang, C.S. Wang, and L.A. Coldren, "High-efficiency, high-speed VCSELs with 35 Gbit/s error-free operation," *Electronics Letters*, 43(19), 1022-1023 (2007).

[2] T. Anan, N. Suzuki, K. Yashiki, K. Fukatsu, H. Hatakeyama, T. Akagawa, K. Tokutome, and M. Tsuji, "High-speed 1.1-μm-range InGaAs VCSELs," *Optical Fiber Communication Conf. (OFC) 2008*, OThS5 (2008).

[3] S.A. Blokhin, J.A. Lott, A. Mutig, G. Fiol, N.N. Ledentsov, M.V. Maximov, A.M. Nadtochiy, V.A. Shchukin and D. Bimberg, "Oxide-confined 850 nm VCSELs operating at bit rates up to 40 Gbit/s", *Electronics Letters*, 45(10) , 501-503 (2009).

[4] L.A. Coldren and S.W. Corzine, *Diode Lasers and Photonic Integrated Circuits*, Chapter 5, Wiley, NY (1995).