Monolithic Arrays of Surface-Emitting Laser NOR Logic Devices

J. I. Song, Y. H. Lee, J. Y. Yoo, J. H. Shin, A. Scherer, and R. E. Leibenguth

***Abstract*—Monolithic cascadable laser logic-device arrays are realized and characterized. The monolithic surface-emitting laser logic (SELL) device consists of an AlGaAs superlattice lasing around 780 nm connected to a heterojunction phototransistor (HPT) in parallel and a resistor in series. Arrays up to 8 × 8 are fabricated, and 2 × 2 arrays show uniform characteristics. The optical logic output is switched off with 40-μW incident optical input.**

TWO-DIMENSIONAL arrays of active optical logic devices have been expected to be the key component for optical switching and optical computing applications. Until recently, research related to the optical logic devices has generally been limited to the passive optical logic devices, such as SEED and its derivatives [1]. However, the successful demonstration of low-threshold electrically driven vertical-cavity surface-emitting lasers [2] opened up the possibilities of two-dimensional active optical devices based on the surface-emitting lasers and other optical switches, such as heterojunction phototransistors (HPT's) or photothyristors. Monolithic and integrated versions of this type of active optical logic device have been reported by several groups [3]–[7], demonstrating the basic optical logic functions, latching, and bistability. Unlike modulator-type passive optical devices, majorities of these active optical logic devices have built-in light sources and cascadability. These advantages will make optical systems rather simple, compact, and robust. Photothyristor-based devices demonstrated very low switching energy owing to the internal feedback of the photothyristor. These devices could be strong candidates for active optical memories. The HPT-based active optical logic gates do not need to control the bias voltage to refresh the logic states, as compared to the photothyristor-based active optical logic gates. As optical logic devices, HPT-based fast NOR logic devices can be most versatile since NOR logic itself and its combinations can generate a complete set of logic family. In this paper, we report a monolithic version of the surface-emitting laser logic (SELL) devices based on a vertical-cavity surface-emitting laser and an HPT connected in parallel. To achieve a parallel operation of NOR SELL, series resistors are also monolithically integrated in the SELL device.

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The SELL device works functionally as NOR and INVERTER. Schematically the SELL device consists of an AlGaAs superlattice surface-emitting laser connected to a HPT in parallel and a resistor in series, as shown in Fig. 1. The SELL device is normally on without input light. When the SELL is in the on state, it is in the lasing mode generating a large optical output. The device can be turned off with input light above certain threshold power. With incident light falling on HPT, the photocurrent is amplified with large gain. Then the HPT starts to sink a large portion of current, thereby limiting the current through the surface-emitting laser below the threshold current level. In this off state, the surface-emitting laser of the SELL is in the light-emitting diode mode, with a small spontaneous emission output. The output intensity ratio between lasing and nonlasing modes ensures a high contrast ratio between the two logic states. Stated characteristics constitute the optical INVERTER function. Also, by shining many inputs into one or many HPT windows (if necessary) one can use it as an optical NOR logic gate.

The SELL structure consists of HPT layers grown on top of superlattice surface-emitting laser layers grown by molecular beam epitaxy on an undoped GaAs substrate. The bottom surface-emitting laser structure has 28.5 pairs of Si-doped $Al_{0.3}Ga_{0.7}As/Al_{0.65}Ga_{0.35}As/AlAs$ quarter-wave layers for the n-mirror and 22 pairs of Be-doped $Al_{0.3}Ga_{0.7}As/Al_{0.65}Ga_{0.35}As/AlAs$ quarter-wave layers on the top as the p-mirror. The active region consists of 14 periods of GaAs(33.9 Å)/AlAs(8.5 Å) superlattice, lasing around 780 nm. Above the surface-emitting laser layers are, from the bottom, a 2000-Å undoped AlAs current blocking layer, a 3000-Å GaAs (Si, 3×10^{18} cm^{-3}) subcollector, a 100-Å AlGaAs (Si, 3×10^{18} cm^{-3}) etch stop layer, a 5000-Å GaAs (Si, 1×10^{16} cm^{-3}) collector, a 1500-Å GaAs (Be, 1×10^{18} cm^{-3}) base, 100-Å undoped GaAs, a 2500-Å $Al_{0.3}Ga_{0.7}As$(Si, 2×10^{17} cm^{-3}) emitter, 500-Å $Al_{0.15}Ga_{0.85}As$(Si, 3×10^{18} cm^{-3}), and a 500-Å GaAs (Si, 3×10^{18} cm^{-3}) contact layer.

Fabrication processes of SELL arrays are as follows: 1) HPT mesas are formed by removing all the layers above the 3000-Å subcollector by selective wet chemical etchings. 2) The first Au/Ge *n*-ohmic contact for the emitter/collector of the HPT and the series resistor is evaporated. 3) Second chemical etching is employed to

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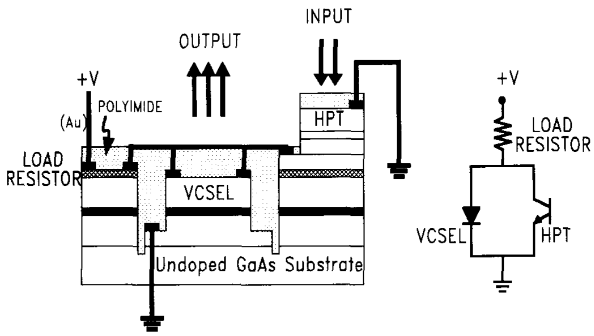


Fig. 1. Structure of the SELL device.

remove the remaining subcollector layer on top of the laser mesa region. During this process, part of the unetched 3000-Å-thick GaAs layer is also defined for the internal series resistor. 4) Au/Zn *p*-ohmic contacts are evaporated for *p*-contacts of the surface-emitting laser electrodes. The window of 8-μm diameter is left open for laser output. 5) Deep trenches (10 μm deep) are then dug out by chemically assisted ion beam etching to isolate individual devices electrically. 6) Another shallow chemically assisted ion beam etching (5 μm deep) is introduced to form circular laser mesas of 18 μm diameter. The resultant mesa-type surface-emitting laser has an annular ring electrode with inner window diameter of 8 μm. 7) The second ohmic contacts for the negative electrodes of the surface-emitting lasers are then made. 8) Polyimide is used to planarize the deep trenches. 9) Via holes for electrical contacts are formed by oxygen-reactive ion etching. 10) The final metallization is done to connect the resistors, HPT's, and surface-emitting lasers. The HPT window has a square opening of 20×20 μm^2. Spacing between the SELL's is 180 μm.

Varius single SELL's having different resistor values, 2×2, 4×4, and 8×8 SELL arrays are fabricated on a wafer. In the same mask, we also include isolated mesa-type surface-emitting lasers and isolated HPT's to characterize the performance of individual parts making the SELL device. The typical threshold current and voltage of the individual surface-emitting laser are 2 mA and 3 V, respectively. The individual laser output power is about 0.1 mW, lasing around 780 nm. The output power is much smaller than expected, partly because of the small window size relative to the mesa diameter. Fundamental Gaussian transverse mode is maintained throughout the lasing operation. The small size (8 μm diameter) of the window with respect to the mesa size (18 μm diameter) might suppress higher transverse modes, thereby limiting the available output optical power. Introduction of deep proton implantation processes instead of deep etching would solve the output power problem. Estimating 64% absorption of incident laser power by the undoped GaAs—the base, collector, and subcollector of the HPT—typical dc current gain of > 40 is observed with 100-μW incident. However, the use of a thinner base will improve the current gain.

To demonstrate the operation of the SELL, the output of a previously reported 770-nm surface-emitting laser [8] is used as an input to the HPT window of the SELL. The threshold optical power to switch the SELL depends on the value of the series resistor. Typical input optical power versus output optical power characteristics of the single SELL devices (zero internal series resistance) connected to various external series resistors are shown in Fig. 2. Resistance and differential resistance of the surface-emitting laser at the operating point are about 2000 and 400 Ω, respectively. The threshold switching power does not decrease significantly for the external series resistors greater than 300 Ω but asymptotically approaches 40 μW. For the minimum optical switching power, the higher the resistance is, the better. But, in that case, thermal dissipation increases accordingly. So in the design of the monolithic SELL device, the optimum value of the series resistance should be determined properly. Initial optical output power of the SELL is set to 60 μW in obtaining Fig. 2. For a typical SELL (1300 Ω integrated series resistance), 60-μW optical output is turned off by introducing 40-μW optical input. To switch the larger optical output power, input optical switching power should be increased accordingly. The threshold optical switching power depends on the optical gain of the HPT and the quantum efficiency of the surface-emitting laser. The small gain and quantum efficiency of the current device limit the system gain of the SELL devices to less than two, which should be improved with layer design and fabrication modification.

In general, 4×4 and 8×8 SELL arrays do not lase uniformly to operate as an array, due to multistep fabrication complexity. But more refined processes would improve the reliability of the arrays. An operation of a 2×2 array with good uniformity is shown in Fig. 3(a). The integrated resistor value for every individual SELL device of the array is 1300 Ω. In Fig. 3(b), one of the 2×2 SELL devices is turned off by shining 50-μW input light from a 770-nm surface-emitting laser [8]. In the upper left pixel (turned off) of the 2×2 SELL array, the rectangular window fo the 20×20 μm^2 HPT filled with the input light can be seen. Simple INVERTER operation is shown in Fig. 4 at the detector-limited speed. The eventual speed of the device might be limited by the speed of the GaAs/AlGaAs HPT, which could be on the order of a few hundred MHz. Introduction of GaAs/InGaP HPT's [9] on top of the surface-emitting lasers could speed up the device even further.

In summary, we designed, fabricated, and demonstrated fully integrated monolithic active optical NOR logic arrays based on surface-emitting lasers and HPT's connected in parallel, as well as an internal resistors in series. Although large-size SELL arrays do not operate uniformly, 2×2 arrays show encouraging operational characteristics with small system gain. The small system gain

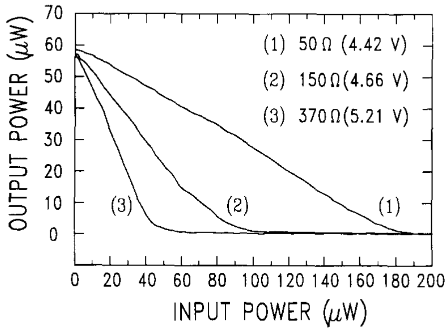
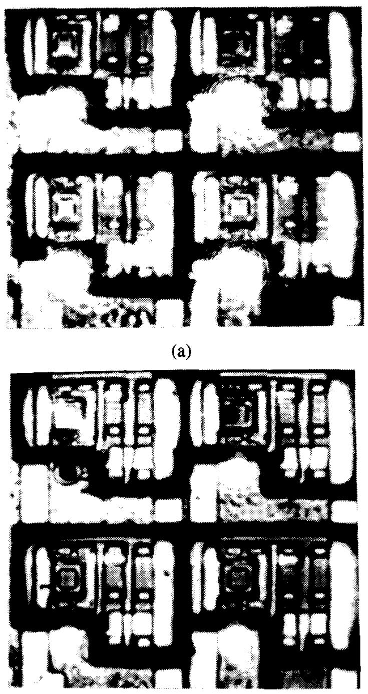


Fig. 2. Typical input optical power versus output optical power of the zero internal series resistance SELL device with various external series resistors.



(a)

(b)

Fig. 3. An operation of a 2 × 2 SELL array.

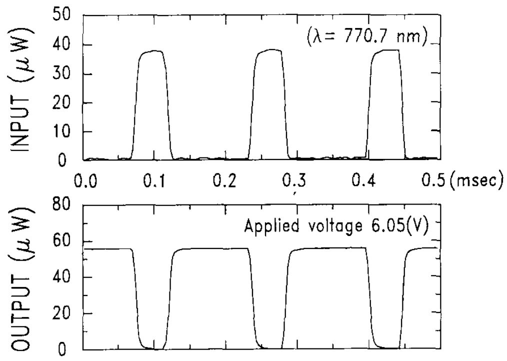


Fig. 4. Simple INVERTER/NOR logic operation of a SELL device. It has 1300 Ω of integrated resistance.

of the SELL leaves room for improvement by increasing the gain of the HPT and the differential quantum efficiency of the surface-emitting laser. The NOR SELL device arrays and their possible derivatives could be used as basic building blocks for future optical switching and optical computing applications.

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