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SURFACE-EMITTING LASER LOGIC

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ABSTRACT

We describe a new class of optical logic devices which consist of integrated phototransistors and surface-emitting lasers. The devices function as optical neurons having high gain and, as arrays, are ideal for neural networks, parallel optical signal processing and optical computing applications.

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SURFACE-EMITTING LASER LOGIC

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Here we describe our efforts to build an ideal optical switch based on the monolithic integration of a heterojunction phototransistor (HPT) with a vertical-cavity surface-emitting laser (VCSEL) diode. To date we have demonstrated high optical gain (> 20 overall, > 200 differential) with the discrete components connected in series. Our devices are ideally suited for parallel optical signal processing which is currently regarded as the most promising research area for achieving significant increases in computational throughput relative to purely electronic based information processing. Parallel optical processing has been severely hampered by the lack of several basic "building block" devices such as optical switching devices that exhibit low-switching energy, high optical gain (fan-out capability) and high contrast. Devices should be: easy to fabricate (use of self-aligned VLSI technology), microscopic in size, and readily integrable with other optoelectronic components without being adversely affected by external optical feedback.

Our basic "unit cell", which we call a surface-Emitting Laser Logic (CELL) device, consists of two components, a photodetector with electrical gain and a low-threshold VCSEL. While each of these components has been demonstrated in prior work,¹⁻² we describe properly scaled, integrable, proton implanted, optimized versions of HPT and VCSEL components and hybrid operation of the pair. In the basic operation of the device, incident light generates photocurrent in the detector element which is internally amplified and then used to drive the laser element above threshold. This optical-electrical-optical conversion is the basis upon which the device achieves insensitivity to external optical feedback (optical feedback to the VCSEL will not affect the input to the HPT). The devices are ideal for high-density, 2-D arrays which convert images from one wavelength to another or from incoherent to coherent light. The CELL also has an important advantage over phototransistor devices; whereas these devices are latching and need to be reset electrically, the CELL does not. Each CELL acts as an independent thresholding optical amplifier. Ultimately our goal is to monolithically integrate the HPT with the VCSEL (see Fig. 1) and then fabricate them into 2-D arrays. Since both the input and output images are directed perpendicular to the arrays, CELLS will be useful for parallel signal processing, multichannel interconnections, neural networks and visual displays. CELLS can also be configured as latching devices, in which case they would function as image memories capable of capturing and storing a 2-D image until the array is reset.

In order to achieve a high-gain optical device that is cascadable and insensitive to feedback, we use the light actuated current switching capability of a high-gain AlGaAs/GaAs HPT and a low-threshold, high-power AlGaAs/GaAs VCSEL. The n-p-n HPT, grown by MBE, consists of a wide-band-gap ($\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$) emitter and narrow-band-gap (GaAs) base and collector regions. The wide-band-gap emitter inhibits the base-to-emitter hole injection current and significantly increases the HPT gain. We electrically isolated the HPTs using shallow proton implants. We employ a bi-layer structure consisting of a layer of electroplated gold covering a layer of photoresist as an ion blocking mask and also as a mask to form self-aligned electrical contacts. The input clear apertures of the HPTs are $15\text{ }\mu\text{m}$ and the implant mask diameters are $50\text{ }\mu\text{m}$. The phototransistor common-emitter, floating-base characteristic exhibits 10 mA photogenerated current for $120\text{ }\mu\text{W}$ of absorbed light power ($176\text{ }\mu\text{W}$ incident) at 800 nm . We measured the frequency response of the implanted HPT using a sync-pumped dye laser and found it to be $> 200\text{ MHz}$ (limited by the bandwidth of the measurement system). The MBE grown VCSELs consist of a 19 period p-type distributed Bragg reflector (DBR), a four quantum-well ($100\text{ }\text{\AA}$) active region and a 27.5 period n-type DBR. We electrically isolated the VCSELs in a manner similar to that used for the HPTs by using deep-proton implants² with $15\text{-}\mu\text{m}$ -diameter implant masks and self-aligned contacts. Implants result in funnel-

ing of the injected current into the VCSEL diode. The CW room-temperature laser diode L-I characteristic exhibits 2.5 mW laser-light output power at 850 nm for 10-mA injection current.

In Fig. 2 we show the calculated energy diagram of a CELL and the equivalent circuit of the integrated structure. R_n and R_p refer to the series resistance of the n-type and p-type mirrors, respectively. R_p dominates the series resistance of the VCSEL resulting in non-ideal laser diode behavior. The large R_p is due to voltage spikes at the AlAs/AlGaAs valence-band interfaces arising from equilibrium charge transfer which are apparent in the energy diagram shown in Fig. 2a. In practice we incorporate ~ 100 -Å-thick $\text{Al}_{0.58}\text{Ga}_{0.42}\text{As}$ steps at each interface of the p-type DBR to reduce this resistance to a level on the order of the n-type mirror.

Figure 1. Illustration of a surface-Emitting Laser Logic (CELL) device in one of its possible configurations.

In Fig. 3 we show the VCSEL diode output power as a function of the input power to the HPT for the pair connected in series as shown in Fig. 2b with an 8.0 V bias. The CELL has both high overall optical gain (> 20 at peak) and high differential optical gain (> 200 at peak). The threshold switching power for the device is $40 \mu\text{W}$ input power and unity gain occurs at $75 \mu\text{W}$ input power. The output power from the CELL saturated at $2800 \mu\text{W}$ for input powers greater than $140 \mu\text{W}$. The on (above threshold)/off (below threshold) contrast of the CELL is 2780, ($40 \mu\text{W}$ input produced $0.9 \mu\text{W}$ output and $120 \mu\text{W}$ input produced $2500 \mu\text{W}$ output). We have also converted 680-870 nm input light to 850 nm output light with our CELLS (note that the range 850-870 nm converts longer wavelengths to shorter). Increasing the Al composition in the emitter and using InGaAs in the col-

lector, base and quantum-well regions of the VCSEL, the wavelength conversion range can be significantly expanded. We also demonstrated cascability of the devices by using optical feedback. A fraction of the VCSEL output power at 850 nm was directed onto the HPT and then the 800-nm input to the HPT was removed at which point we observed latching of the CELL.

Figure 2. a) Calculated energy diagram of the integrated HPT/VCSEL (The diagram in a) is to scale with the exception that the 4-QW active region is expanded five times), and b) equivalent circuit of the optical neuron. R_n = resistance of n-mirror, R_p = resistance of p-mirror, V_0 = bias voltage. Only the lowest-energy conduction band is shown, i.e. the Γ -valley is shown for the GaAs layers while the X-band is shown for AlGaAs layers with Al compositions of 1.0.

Figure 3. Room-temperature CW output power versus input power of a CELL. The HPT and VCSEL are connected in series as shown in Fig. 2b with the HPT in the floating-base configuration. The input and output wavelengths are 800 and 850 nm, respectively. The output diameter of the VCSEL is 15 μ m. Input power has been corrected for reflection loss at the air/GaAs interface.

In conclusion, we have described a new device ideal for applications that require high-optical gain, cascadability, and insensitivity to external optical feedback. CELLS can be operated as optical switching, optical bistable, or light amplification devices. To date we have demonstrated high optical gain using discrete components connected in series. We are presently fabricating 2-D arrays of devices in which the HPT and VCSEL diode are monolithically integrated. A natural application for these arrays are neural networks. Using a holographic optical element, one can realize a global configuration of an optical neural network in which CELLS perform optical neuron functions. Another property of the CELL worth exploring is the intermediate connection between the VCSEL and HPT. This internal connection provides us with additional flexibility in choosing the nature of the input and output optical signals. For example, CELLS can be configured as latching devices by allowing optical feedback via the high reflector at the HPT-VCSEL interface, in which case, as arrays, they would function as image memories capable of capturing and storing images. These devices can perform Boolean algebraic functions such as AND, OR using two beam combinations or as XOR by combining CELLS and HPTs. The slope of the output versus input curve can be modified to be either binary-like for digital functions or sigmoidal-like for neural functions (the curve shown in Fig. 3 is nearly sigmoidal and as such suitable for neural-network functions). As a final example, $N \times N$ out-of-plane arrays of individually addressable Wannier-Stark modulators³ may be used to control inputs to arrays of CELLS (the input intensity for the HPT is below the excitonic saturation intensity of the Wannier-Stark modulators).

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