Optical properties of selectively oxidized vertical cavity laser with depleted optical thyristor structure

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The authors show that the optical properties of selectively oxidized vertical cavity lasers with a depleted optical thyristor structure have a low threshold current and high sensitivity to input optical light. The oxidized thyristor laser clearly shows a nonlinear s-shaped current-voltage and lasing characteristics. A switching voltage of 5.24 V, a holding voltage of 1.50 V, and a very low threshold current of 0.65 mA are measured, making these devices attractive for optical processing applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2355362]

Technical advances in optical semiconductor devices have permitted fabrication of two-dimensional surface-normal optical devices. Two-dimensional vertical cavity surface-emitting lasers (VCSELs) show promise in the area of optical interconnections and parallel data processing. A candidate device for optical data processing is a VCSEL forming a vertical-to-surface transmission electrophotonic device, in which the functions of optical computing, optical switching, optical memory, and optical logic have been attained.[1–3] Using these functions, reconfigurable and optically addressable interconnections have been proposed which are capable of creating multistage networks through cascaded devices.

The previously reported *p-n-p-n* optical thyristor devices, which used a charge sheet layer with a high doping concentration in the center region, have relatively slow-switching speed. In these devices, excess majority carriers in the center layers of the on-state devices cannot be depleted immediately because they are confined and vanish only by very slow recombination process (approximately milliseconds). This serious slow-switching problem has been overcome by the depleted optical thyristor (DOT),[4] in which excess carriers in the center *n* and *p* layers are fully depleted by applying a reverse-bias pulse. When a negative voltage pulse is applied, the center layers of the DOT are fully depleted, and the excess carriers can be swept out in less than a few tens of picoseconds. Hence the DOT is a simple and fast two-terminal optical device.

In the structure reported here a low doped center layer is used instead of the highly doped charge sheet layer, so it can be completely depleted of charge by reversely biasing the *p-n* junction enabling fast switching speed.[5] Moreover, using selective oxidation of a buried AlGaAs layer to define the laser aperture will produce low threshold current, because of reduced current spreading and elimination of leakage current through the sidewalls.[6,7] This selectively oxidized laser also has a high sensitivity to optical input light, because it is transparent to the injected input light signal which is absorbed in the active region. In this letter, we report the lasing characteristics of the selectively oxidized vertical cavity laser with the depleted optical thyristor (VCL-DOT) structure which exhibits a low threshold current and is sensitive to the optical input light.

Figure 1 shows the structure of the 850 nm VCL-DOT which was grown on *n*-GaAs substrates by metal organic chemical vapor deposition. The active region contained the following layers: a n^+-$Al_{0.4}Ga_{0.6}As$ cathode layer (240 nm, Si doped at 5×10^{18} cm^{-3}), a *p*-$Al_{0.15}Ga_{0.85}As$ layer (200 nm, C doped at 2×10^{17} cm^{-3}), a three-quantum-well GaAs undoped layer (7 nm) with barrier $Al_{0.3}Ga_{0.7}As$ undoped layer (10 nm), a *n*-$Al_{0.15}Ga_{0.85}As$ layer (200 nm, Si doped at 2×10^{17} cm^{-3}), and a p^+-$Al_{0.4}Ga_{0.6}As$ anode layer (240 nm, C doped at 5×10^{18} cm^{-3}). The *p-n-p-n* triple junction active region surrounded by two distributed Bragg reflector mirrors consiss of $Al_{0.9}Ga_{0.1}As/Al_{0.16}Ga_{0.84}As$ layers

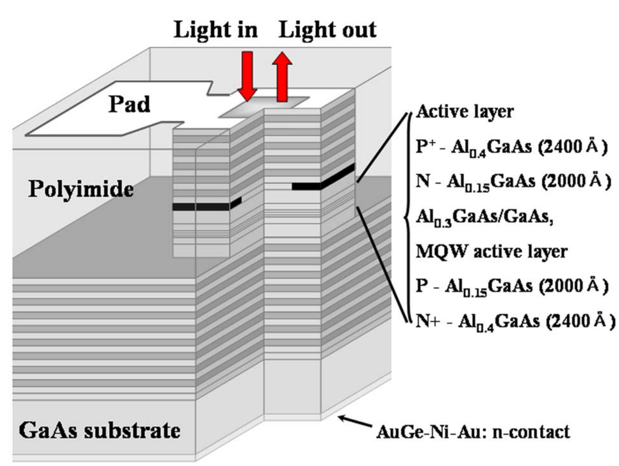

FIG. 1. Cross section of the oxidized vertical cavity laser with the depleted optical thyristor structure.

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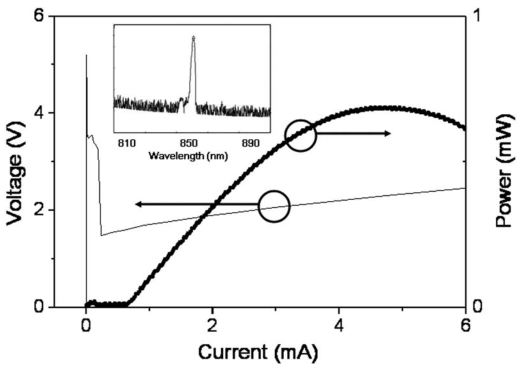

FIG. 2. Light-current (heavy) and current-voltage (light) curves of a $2 \times 2\ \mu m^2$ VCL-DOT. The inset shows the lasing spectrum at 4 mA.

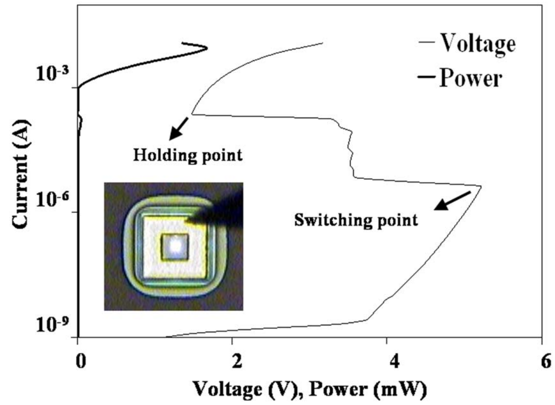

FIG. 3. Light-current (heavy) and current-voltage (light) curves of the VCL-DOT. The inset shows the top view of the VCL-DOT with lasing.

with linearly graded transition layers. The alloy composition grading allows reduction in the series resistance of the devices. There were 21.5 periods in the top mirror (C doped at 2×10^{18} cm^{-3}) and 40 periods in the bottom mirror (Si doped at 2×10^{18} cm^{-3}). A *p*-AlGaAs oxide layer (300 nm, C doped at 2×10^{18} cm^{-3}) for confining the current and the light was grown between active layer and the top mirror. A *p*-GaAs cap layer (C doped at 1×10^{19} cm^{-3}), which also acts as a phase-matching layer, was grown on the surface of the top mirror. The cavity space between the top and the bottom mirrors is 4λ, where λ is the emission wavelength in the semiconductor medium. This device structure allows either electrical or optical switching from the off state to the on state. During the on state the DOT has low impedance and emits laser light. To increase the efficiency of optical emission, three undoped multiple quantum well layers have been incorporated in the active region of the VCL-DOT. The active region also acts as an absorption region for optically switching the VCL-DOT. Although the active region is thin, enhancement of absorption is expected because of multireflection between the two mirrors. Design parameters such as doping concentration and layer thickness of the each active layer were simulated using a finite difference method.[8,9] The top Ohmic contact was fabricated using a lift-off process of Ti–Au (20nm/150 nm), and the bottom was contacted with AuGe–Ni–Au (40 nm/20 nm/150 nm) located on the substrate. To pattern the devices, reactive ion etching was used to etch square mesas ranging in size from 30×30 to $60 \times 60\ \mu m^2$ with a size variation of 0.5 μm. The VCL-DOTs are then placed in a wet thermal oxidation furnace to laterally oxidize the current confinement layer and anneal the Ohmic contacts.

Figure 2 shows the light-current and current-voltage characteristics of room-temperature continuous wave operation. The oxide confined VCL-DOT grown on *n*-type substrate had square current apertures approximately $2 \times 2\ \mu m^2$. The 0.65 mA threshold current is lower than previous reports. The single mode spectral response of the optical output of the selectively oxidized VCL-DOT is shown in the inset of Fig. 2. The emission wavelength is 854.5 nm. Figure 3 shows a log plot of the light-current and current-voltage characteristics of a VCL-DOT with an oxide aperture of $5 \times 5\ \mu m^2$. The inset in Fig. 3 shows the top view of the VCL-DOT while lasing. For forward bias, the optical thyristor clearly shows the nonlinear s-shaped current-voltage characteristic with three distinct states: the low-current off state, the high-current on state, and the negative resistance region. In the off state, the device has high impedance up to a switching voltage of 5.24 V and has low impedance for the on-state voltage of 1.50 V. The switching and holding currents are 5 and 100 μA, respectively. The oxidized devices have a low holding power and high sensitivity to optical input light.[10]

Figure 4 is a log plot of the current-voltage characteristics of the VCL-DOT with an oxide aperture of $5 \times 5\ \mu m^2$ as a function of input light intensity causing a switching transition. The switching voltages are clearly decreased from 4.86 to 1.90 V as the external optical input intensity changes from zero to 500 μW. The required optical input power should be lower than the values given in Fig. 4, because the window size of VCL-DOT is $10 \times 10\ \mu m^2$, while the values shown in Fig. 4 are calibrated using a multimode fiber with a diameter of 50 μm and a photodetector with a window size of $100 \times 100\ \mu m^2$. The switching and holding voltages do not significantly vary with differing oxide aperture and mesa area. In previous work, high sensitivity and low holding power are achieved by passivating the device perimeter with a regrowth of AlAs.[10,11] This is because the switching current for unpassivated devices is proportional not to the area, but to the perimeter of the device. The VCL-DOT reported here can achieve high sensitivity without any additional passivation process. It is expected that reduction of the size of the oxidized lasers will lead to a linear decrease of the switching and holding currents and of the input light, which is an important consideration for closed packaged two-dimensional arrays of such devices.

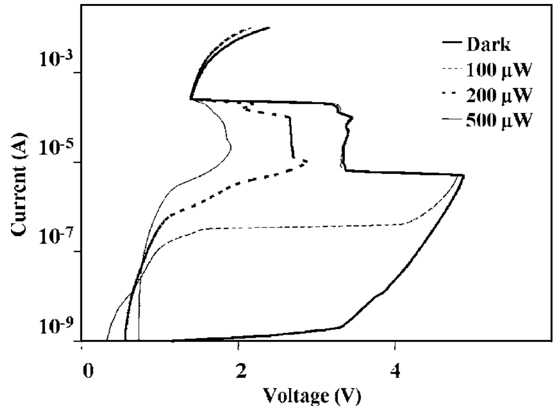

FIG. 4. Current-voltage curve of the VCL-DOT with an oxide aperture of $5 \times 5\ \mu m^2$ as a function of input light intensity.

In conclusion, we have demonstrated a VCL-DOT grown on *n*-type substrate fabricated by selective oxidation. The *p*-*n*-*p*-*n* optical thyristors clearly show a nonlinear s-shaped current-voltage and lasing characteristics. A sufficient switching voltage and very low threshold current are obtained. Our experimental results suggest the potential applications of VCL-DOT in advanced optical communication systems. For a practical use of the DOT in a free space optical interconnect, further improvements are required in optical sensitivity and emission efficiency.

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