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Multi-quantum-well zero-gap directional coupler with disordered branching waveguides

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A nonlinear switch formed by the integration of an overmoded multi-quantum-well (MQW) section with disordered input and output branching waveguides is presented. The area-selective disordering of GaAs/AlGaAs MQWs is achieved by diffusion of group III vacancies generated by etching of the surface oxide. The absorption edge of the disordered MQW regions was shifted by 71 nm and the disordered ridge waveguides had a loss figure of 8 dB/cm. Time-resolved optical pump-probe measurements were performed on an integrated switch that had more than a 5:1 power split between the two output ports. The measured signal recovery of the switch had a time constant of 110 ps.

In order to integrate optical and optoelectronic devices on a single substrate, materials with different optical and optoelectronic properties need to be controllably defined at different locations. A popular method of achieving photonic and optoelectronic integration is by selective area epitaxial regrowth using molecular beam epitaxy or metalorganic vapor phase epitaxy. However, this method requires extensive growth capabilities, and a potentially much simpler postgrowth method is the selective area disordering of multi-quantum-well (MQW) structures. Postgrowth processing of the MQWs can result in a significant blueshifting of the effective absorption edge, thus altering the properties of the material. The controlled disordering of MQWs has been studied extensively and a number of processing techniques have been developed.[1–4] In the most promising methods, the disordering of the MQWs is induced by the diffusion of group III vacancies. In these cases, the disordering process does not alter the as-grown impurity doping profile. Previous reports of impurity-free vacancy disordering of GaAs/AlGaAs MQWs have relied on the formation of Ga vacancies formed at the sample surface due to the preferential absorption of Ga atoms by a SiO_2 cap layer when the sample is subjected to a rapid thermal annealing at elevated temperatures. Another method employs As ion implantation[3,4] to produce damage and therefore vacancies. Rapid thermal annealing then causes the intermixing of Ga and Al atoms in the wells and barrier layers.

In this letter, we describe a simpler method of realizing impurity-free vacancy induced disordering of quantum wells. We employ this new technique to demonstrate the first all-optical switch with a MQW mode switching section integrated with disordered, low-loss input and output waveguide sections. The switching characteristics of this integrated zero-gap directional coupler[5] are presented. Photoluminescence (PL) characterization indicates that blueshifting of the peak emission wavelength by as much as 70 nm can be achieved by this intermixing method.

The waveguide structure was grown by molecular beam epitaxy (MBE) on an undoped GaAs substrate. It consisted of a 2 μm thick $Al_{0.3}Ga_{0.7}As$ lower cladding layer grown on the substrate followed by the MQW waveguiding layer, then a final 0.5 μm thick $Al_{0.3}Ga_{0.7}As$ top cladding layer. The MQW layer was made up of 38 periods of 70 Å thickness GaAs layers alternating with 70 Å wide $Al_{0.3}Ga_{0.7}As$ layers.

In order to assess the intermixing process, small cleaved samples (3 mm$\times$4 mm) were first cleaned by boiling in acetone and methanol and then processed for controlled disordering of the MQWs. The technique is based on preliminary measurements described in Ref. 6 The surface was oxidized by heating in air for 30 min at 600 °C. This surface oxide was then removed by etching in concentrated hydrofluoric (HF) acid for 15 min thus creating surface vacancies. After rinsing in de-ionized water, the samples were immediately annealed at 615 °C for 3 h in a tube furnace with a constant flow of high purity nitrogen gas. A piece of freshly cleaned GaAs substrate was used to cover the samples in order to minimize As loss during the annealing stage.

A control sample was oxidized in the same manner and the surface oxide was etched off. However, prior to the final annealing stage, this sample was dipped in hydrogen peroxide solution for 10 min in order to neutralize the vacancies.

The MQWs (as-grown and disordered) were characterized by room temperature PL measurements. The PL spectra of Fig. 1 indicate that the disordering of the MQW by the oxidation, etching, and annealing process can result in a blueshift of the band-gap wavelength from 820 to 745 nm.

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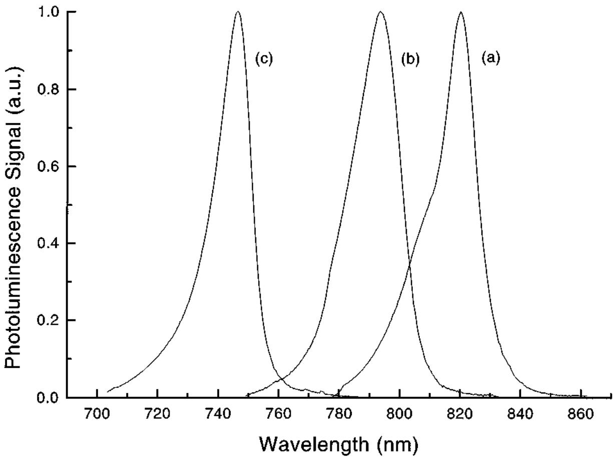

FIG. 1. Room temperature photoluminescence spectra of the MQW samples: (a) from as-grown sample; also from the H_2O_2 treated sample (b) from the sample that was oxidized, etched, and annealed for 2.5 h, (c) from the sample that was oxidized, etched and annealed for 3 h.

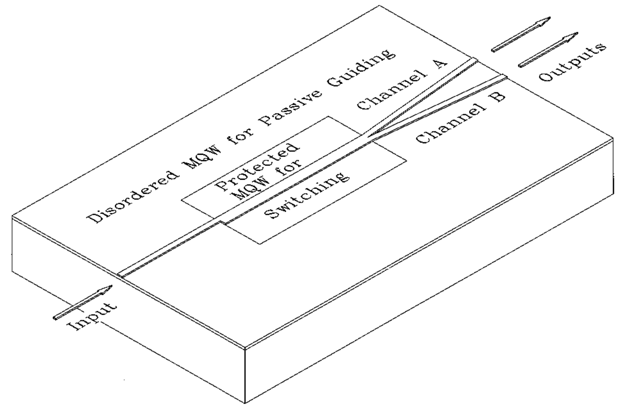

FIG. 2. Schematic drawing of integrated all-optical switch with disordered and nondisordered MQW sections.

The control sample that was treated with the H_2O_2 solution emitted a PL spectrum that was indistinguishable from the as-grown one.

Removal of the surface oxide from the top of AlGaAs cladding layer appears to result in a high density of group III vacancies at the surface. These vacancies are driven into the MQW region by thermal annealing thereby resulting in intermixing of Ga and Al atoms as these randomly exchange lattice positions with the vacancies. The process is simple, controllable, and very reproducible, and leads to a large shift in the effective band edge of the MQW layer.

Subjecting the oxide-etched sample to a solution of H_2O_2, effectively protects the MQWs from disordering during the annealing cycle. It is believed that the H_2O_2 causes rapid reoxidation to the surface and hence removes the vacancies. This is a very important property that allows devices with different optical band gaps to be fabricated on the same MQW sample.

Ridge waveguides were fabricated by defining 4 μm wide strips and etching off 0.45 μm from the cladding layer over the rest of the sample surface. A narrow bandwidth ($<$1.5 GHz) cw Ti:sapphire laser was used to measure the propagation loss of the disordered waveguides. The thermo-optic effect in the waveguide was employed to scan the Fabry–Perot fringes by gentle heating and the optical loss deduced from the measured visibility (maximum to minimum intensity) of the interferogram.[7] Using this technique, the propagation loss of the ridge waveguides fabricated from the disordered MQW layer was deduced to be 8 dB/cm at 850 nm wavelength. This is attributed to scattering losses due to surface roughness.

The integrated all-optical switch shown in Fig. 2, consists of a dual-mode MQW waveguide section with disordered input and output single mode waveguides. The sample was first thermally oxidized and then the surface oxide layer was removed as described above. A photoresist film with a 200 μm$\times$500 μm window was deposited on the sample using conventional photolithographic techniques. The sample was then immersed in hydrogen peroxide solution for 10 min to neutralize the surface vacancies in the open window. The photoresist film was removed and the layer was annealed in the tube furnace at 615 °C for 2.5 h to create the disordered regions. Using a second stage photolithographic process, the device was then delineated such that the central mode switching region was aligned inside the previously windowed section. A 1:1:10 phosphoric acid, hydrogen peroxide, and water solution was used to etch off 0.4 μm of the cladding layer and form the waveguide cladding ridges. The sample was cleaved to a total length of 1.3 mm.

The 2.5 h annealing time resulted in a disordering shift of the exciton peak from 820 to 793 nm, as shown in the PL spectrum of Fig. 1(b). On the other hand, the regions of the MQW which were protected by soaking in the H_2O_2 solution showed only a very slight blueshift of 2 nm in the PL peak emission. Due to a small fabrication misalignment, the protected area extended beyond the overmoded waveguide section and the 200$\times$500 μm window was undercut by the H_2O_2 solution which resulted in about 50 μm of the input waveguide remaining nondisordered.

The switching characteristic of the device was measured using an optical pump-probe setup. Wavelength tunable, 1 ps pulses were obtained from a Coherent 702 styryl-9 dye laser pumped by a frequency doubled, cw mode-locked Nd:YAG laser. The pump beam was polarized in the TE (horizontal) configuration while the mechanically chopped probe beam was polarized in the TM (vertical) direction. The two beams were recombined colinearly and focused into the input waveguide. The light at the output of the device was collected by a microscope objective lens and imaged onto a CCD camera. A polarizer placed at the output of the waveguide was used to filter out the pump beam. The throughput of the probe beam from either output port was measured by a silicon photodetector with a small aperture. Lock-in detection was used to measure the probe beam in either output port as a function of time delay between the pump and probe pulses.

A typical result of the time-resolved optical pump-probe measurements of the all-optical switch is shown in Figs. 3(a) and 3(b). The excitation wavelength for these data was 849

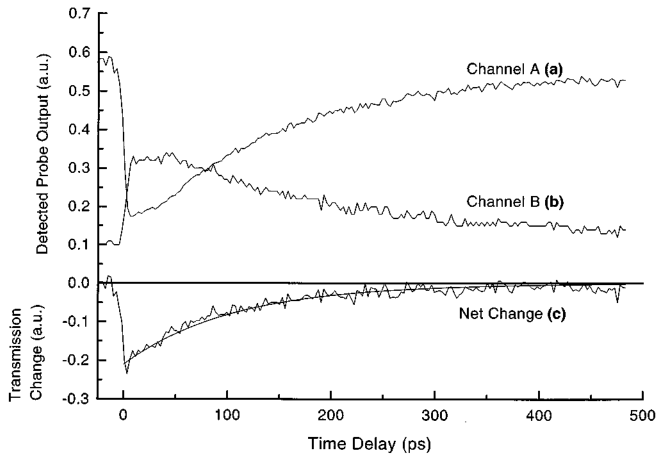

FIG. 3. (a) and (b) Switching of the probe transmission through the two output channels A and B, respectively, as a function of time delay with the pump pulses. (c) Nonlinear transmission component of the pump-probe signal deduced by summing the total probe signal in channels A and B.

nm and the energy of the pump pulses was around 30 pJ coupled into the input waveguide. The probe signal, which normally exits from output channel A in the absence of the pump pulses, was switched into port B, when the pump pulses temporally overlapped with the arrival of the probe pulses.

The pump-probe measurements revealed a switching contrast of 3:1 in the nonoptimized device. The single-mode input waveguide excites two copropagating modes in the central section. These modes have different phase propagation constants and hence they interfere at the output and produces an intensity pattern that depends on the phase difference between them.[8–10] The single-mode output waveguides serve to collect the optical intensity on the right and left region of the central switching section. Under normal low power conditions the mode mixing results in 85% of the light emerging from channel A. However, a strong pump pulse causes a carrier induced nonlinear refractive index change in the switching section and the phase difference between the two modes is changed in a manner that 60% of the signal now exists from channel B. The recovery time constant of the switch was deduced to be 110 ps from the probe signal recoveries shown in Figs. 3(a) and 3(b). This is much shorter than expected for carrier recombination in GaAs/AlGaAs MQWs and since the sample was undoped, there is no electric field to cause carrier sweep-out from the QWs. It most likely arises from rapid recombination of the optically generated carriers due to some vacancies being generated in the MQW switching region.

The power transfer was not symmetrically divided between the two output channels due to nonlinear absorption in the nondisordered region of the input waveguide. The total contribution of the nonlinear absorption can be obtained by summing the two curves in Figs. 3(a) and 3(b). The signal due to the nonlinear switching of the modes can then be extracted by subtracting half of the signal due to nonlinear absorption from the measured data, as shown in Fig. 3(c). The recovery of this nonlinear absorption is the same as for the optical switching and therefore confirms that it also arises from optically generated free carriers.

A new technique of MQW disordering by diffusion of Al and/or Ga vacancies created by the etching of Al and/or Ga oxide on the sample surface has been developed. This method is impurity-free, area selective, low cost, easy to perform, and highly reproducible.

Integration of a nonlinear coupler with disordered, low-loss, branching waveguides has been demonstrated using the above technique. A zero-gap directional coupler switch was chosen for integration because it has the advantage of a particularly short switching length. The switch shows a fast 100 ps recovery, which could be further improved by employing carrier sweep-out in an electric field[11] or by creating additional defect centers for nonradiative recombination.[12] This new technique shows good potential for extending integration to a number of waveguide optoelectronic components and circuits on a single semiconductor chip.

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