Novel 2×2 Wide-Angle AlGaAs/GaAs Carrier-Injection Optical Switch with Reduced Power Consumption

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Abstract: We demonstrate a 2×2 AlGaAs/GaAs optical switch based on our wide-angle design including current-spreading restriction, curved electrodes, double-reflection interfaces, and graded heterojunctions. The fabricated device has a 7° crossing angle and a 0.6W power consumption.

OCIS codes: (130.4815) Optical switching devices; (130.3120) Integrated optics devices.

1. Introduction

Fast optical switches have important applications in advanced optical networks, such as transferring and routing burst and packet-based optical signals. Carrier-injection type semiconductor digital optical switches (DOSs) are very attractive candidates due to their small size; nanosecond switching times; immunity to variations in temperature, wavelength, polarization, etc; and the ease with monolithic integration. Their drawbacks, however, are high insertion loss and excessive power dissipation. Recently, reconfigurable waveguide DOS devices with small switching current and low crosstalk have been reported [1,2], but their branch angle is only 0.9°. Carrier-induced total internal reflection (TIR) has been widely used to increase the deflection angle for high integration density [3]. To achieve the large index modulation (~ 0.01) required for TIR switches, many efforts have been made to confine carriers to the required index change regions using relatively complex semiconductor device technologies, such as ion implantation, electron-beam lithography, Zn diffusion, and epitaxial regrowth [4,5].

In this paper, we present the design, fabrication, and characterization of a novel 2×2 wide-angle AlGaAs/GaAs TIR optical switch by only using conventional semiconductor fabrication technologies. To release the tight requirements on the width of the electrodes located at the 2×2 switch centre, a novel double-reflection switch design is proposed and demonstrated. Switching performance is further improved by applying curved electrodes, carrier-restriction gaps, and compositionally graded heterojunctions.

2. Switch Design

The series of pictures shown in Fig.1 below illustrate our approach to improve the performance and reliability of a 2×2 TIR optical switch with a double-reflection electrode geometry. In the conventional electrode design as shown in Fig.1(a), in order to reduce the axis misalignment of the reflected light, the electrode has to be narrow, but this narrow electrode will lead to the degradation of the extinction ratio due to poor reflectivity induced by current passing through the electrode. A bow-tie electrode design as shown in Fig.1(b) has been reported to increase the deflection angle without causing significant adverse effect on the reflectivity, extinction ratios, and scattering loss [6]. However, its electrode is still narrow at the centre and part of the incoming light that incidents on the second segment may be refracted because of the increased incident angle. All these limit the crossing angle of bow-tie type 2×2 switches to 2° in real device applications. Fig.1(c) shows our novel design of the double-reflection electrode. This electrode structure would eliminate the "misalignment" and electrode width problems mentioned before. With

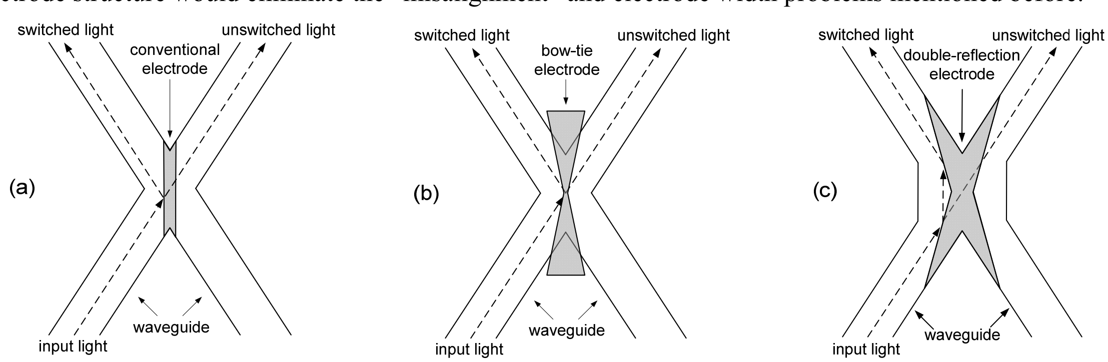

Fig.1. Schematic diagrams of 2x2 TIR optical switches. (a) with a conventional electrode design; (b) with a bow-tie electrode design; (c) a new double-reflection electrode design that can increase deflection angle, reduce optical axis shift, and switching threshold.

this configuration, the light incident on the first electrode segment at a half of the switch cross angle is reflected toward the second electrode segment, which further reflects the light at another half of the switch cross angle toward the designed output port. As a result, at the same switch crossing angle, the TIR required index change (and hence the injection current density) needs to be only half that of the earlier "single reflection" design. On the other hand, if the same switching current density is to be used, the switch crossing angle can be doubled, making the overall device more compact and thus allowing more devices to be integrated on the wafer. The main drawbacks of the double-reflection design are the high switching current associated with the increased electrode area, and the scattering loss due to the complex structure inserted at the switch centre. These two deleterious effects drop dramatically by increasing the switch cross angle, and can be eventually controlled to an acceptable level at large deflection angle.

A schematic layout of our proposed switch structure is shown in Fig.2. As shown in the figure, the double-reflection design enables us to set the electrode width at several times larger than the light penetrating depth and hence provide a sufficient index change for TIR and large extinction ratio. Each of the four segments of our switch electrode is curved in a logarithmic spiral shape instead of the conventional straight electrode. This electrode-curvature has been theoretically studied and reported that it could provide high power reflectivity, high extinction ratio, and low scattering loss [7]. At the TIR interface inside our switch design, a small isolation gap is introduced between the electrode and waveguide to obtain a sharp carrier gradient profile for improved switching efficiency. A double mask technique is used to overcome photolith problems when forming small gaps. With this technique, two masking stripes, which are independently defined in separate lithographic steps, can also be used as masks in the dry etch process to obtain ridge waveguides with small isolation trenches. The curved waveguide sections are cosine-bends with the functional form as $h/2-(h/2)\cos(\pi x/l)$, where h is the height of the bend, l is the length of the bend, and x is the horizontal propagation length. To reduce the crosstalk at the waveguide crossing, adiabatic tapers are used in the crossing region. This waveguide widening can also provide more fabrication freedom on the electrode.

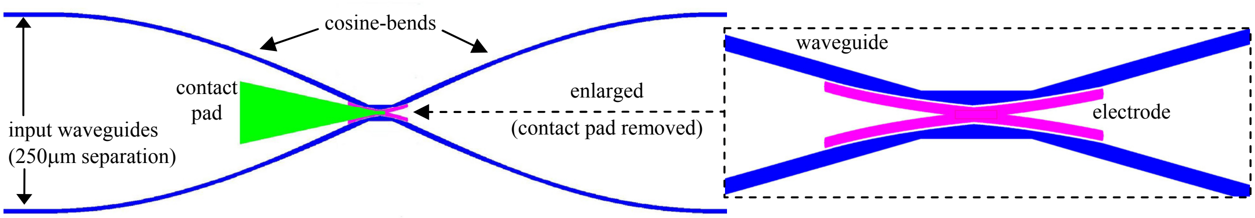

Fig.2. Schematic layout of proposed 2x2 double-reflection TIR optical switches

3. Switch Fabrication and Characteristics

The waveguide layer structure, consisting of six AlGaAs/GaAs layers grown by MOCVD on n+ GaAs substrates, is shown in Fig.3. For a single-mode waveguide, the optimized ridge width is 5.0 µm. The 1.7 µm thick core layer is the largest ever reported for a single-mode semiconductor DOS. It provides high coupling efficiency to a single-mode fibre. This core layer is lightly doped to compensate between low propagation loss and low switching voltage. Since the constituent heterojunction band discontinuities would impede the current across the junction, 20nm-40nm thick, compositionally graded interfaces were used at all the layer interfaces to reduce the switching voltage. As we reported in [8], the effect of using graded heterojunctions in reducing the switching voltage is quite significant.

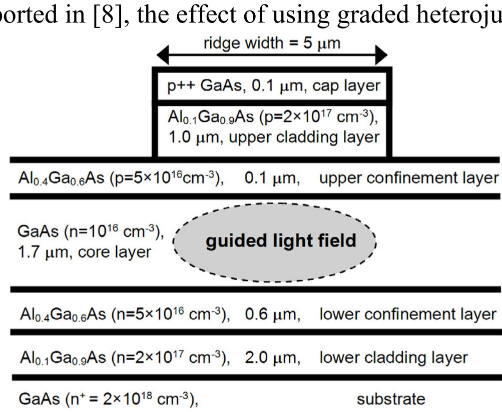

Fig.3. Optimized waveguide layer structure.

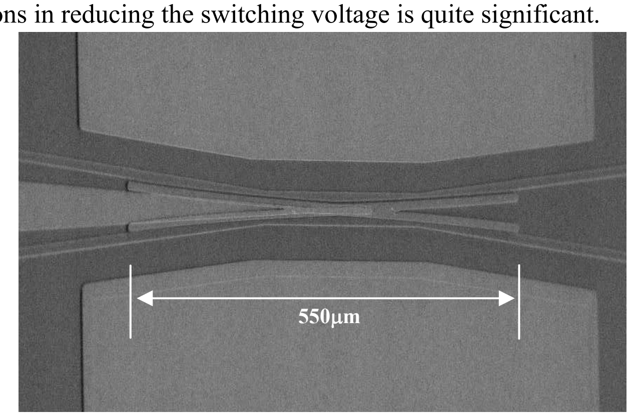

Fig.4. SEM image of a fabricated 2×2 double-reflection TIR optical switch.

Based on this waveguide layer structure, we have fabricated a prototype 2×2 carrier-injection optical switch based on the double-reflection design. Fig. 4 is a SEM image of the fabricated switch with the input waveguides on the left, viewed from an angle. It should be noted that the fabrication processes only employ conventional technologies, such as UV photolithography, e-beam evaporation and plasma etching. Independently formed electrode and photoresist layers were used as a double-mask in a single dry etch process to form the ridge waveguides and gaps. Uniform gap spacing was obtained using vernier alignment marks with ± 0.1 μm alignment accuracy. Fig.5 is a SEM picture of the fabricated carrier-restriction gap, with the sample cleaved at a location close to the branching vertex of output waveguides.

The fabricated switch has an electrode length of 550 μm, a waveguide crossing angle of 7°, and a cosine-bend section of 6.4 mm. The measured propagation losses of straight waveguides with undoped and lightly doped core layers are 0.3 dB/cm [9] and 1.5 dB/cm, respectively, for a wavelength of 1.55 μm. Fig.6 shows measured switching curves for light coupled into the top left input port. The switched state was obtained for an injection current of 220 mA. At this state, the driving voltage was 2.89 V and the measured device series resistance was 9.8 Ω. So the total power dissipation was at a manageable level of 0.6 W. With the area of the fabricated electrode being 3400 μm^2, the corresponding switching current density was 6.5 kA/cm^2. By using this current density and assuming a 10 ns carrier life time, the estimated carrier density and Δn are about 2×10^{18} cm^{-3} and -0.02, respectively. Such a high index change may be the result of two facts: one is that the carrier life time is quite long in the thick core layer; the other is that the current spreading decreases at very high current densities which results in current "bunching" in the core below the isolation gap and hence yields better power reflectivity. The measured switching time is 15 ns. On-off extinction ratio is 13 dB for the through port and 14 dB for the switched port. The switch is wavelength independent for a wavelength range from 1540 nm to 1570 nm. A very small polarization dependence of TE and TM modes has been observed (<0.5 dB). The measured extra insertion loss of the 2×2 switch compared with the straight waveguide fabricated on the same chip is 3dB.

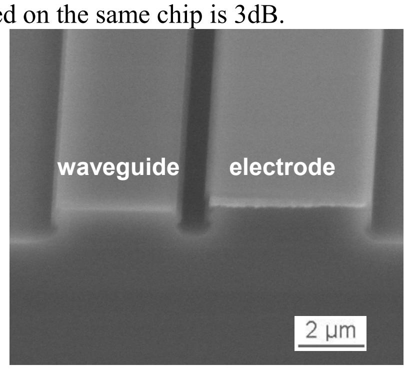

Fig.5. SEM image of the carrier-restriction gap.

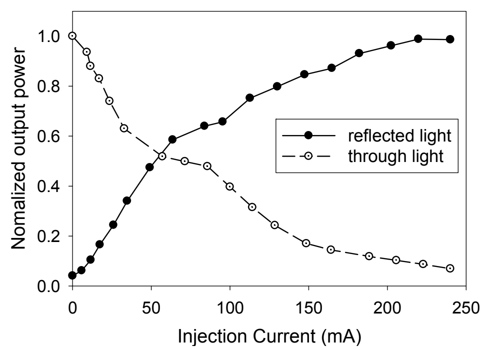

Fig. 6. Typical measured switching characteristics vs. dc driving current.

4. Conclusions

Based on a novel structure design, a wide-angle 2×2 AlGaAs/GaAs TIR optical switch has been developed by using only conventional semiconductor fabrication technologies, suitable for monolithic circuit integration. The switch has a waveguide crossing angle of 7°, a manageable maximum dc power consumption of 0.6 W, and can serve as a basic block for high dense switching matrices. The employed techniques, such as double-reflection interfaces, carrier restriction gaps, curved electrodes and graded heterojunctions, can be applied to switches based on other materials.

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