Push–Pull Fused Vertical Coupler Switch

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***Abstract*—A single-electrode push–pull fused vertical coupler (FVC) switch using macroscopic crystal inversion symmetry is demonstrated. The anisotropic linear electrooptic effect in a zinc-blende crystal is used to achieve optical switching under 12-V reverse bias for a 6.9-mm-long FVC whose two guiding layers have different crystal symmetries. No switching is observed for the identical structure in which the two guiding layers have the same crystal symmetry.**

***Index Terms*—Electrooptic effects, optical directional couplers, optical switches, water bonding.**

VERTICAL directional couplers [1]–[3] are very attractive candidates to make optical waveguide switches and narrowband filters because of their very short coupling length and the feasibility of integration with other optoelectronic devices. Generally, switching is achieved by introducing a phase mismatch $(\Delta\beta)$ between two waveguides through the electrooptic effect. In a push–pull operation, the introduction of positive and negative phase shifts in the two waveguides of the coupler reduces the driving voltage and chirping for switching. It is well known that the linear electrooptic effect is anisotropic [4], [5] in zinc-blende crystal structures. When the applied electric field is perpendicular to the (001) surface, it gives a positive index change $+\Delta n$ for the TE-polarized light propagating along [110] direction and a negative index change $-\Delta n$ for the light propagating along the $[1\bar{1}0]$ direction. In conventional epitaxial vertical couplers, the upper and lower waveguides have the same crystal orientation [see Fig. 1(b)]. Consequently push–pull operation requires the signs of the electric fields in the upper and lower waveguides to be opposite. This requires presence of a third electrode between waveguides and application of positive and negative biases to the upper and lower waveguides. The fabrication is difficult in conventional vertical couplers. Since the electrooptic effect is anisotropic, if one of the waveguides in the vertical couplers is along the [110] orientation and the other one along the $[1\bar{1}0]$ orientation [see Fig. 1(a)], then under an applied bias, the index changes in two waveguides have different signs. This simplifies the electrode fabrication and only requires one electrode for push–pull operation. In this letter, a vertical coupler switch with macroscopic inversion symmetry is demonstrated that uses the wafer fusion technique.

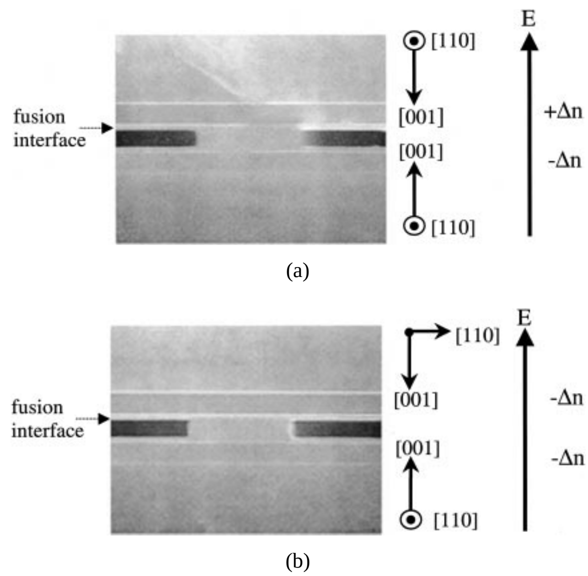

Fig. 1. SEM pictures and the crystal orientations of (a) antiphase FVC and (b) in-phase FVC.

Wafer fusion [6], [7] is a powerful technique to fabricate optoelectronic devices that cannot be realized using conventional epitaxial growth and processing. In addition to the inherent advantage of combining two materials with a large lattice mismatch, wafer fusion has another unique feature to integrate two wafers with various crystallographic orientations. For (001) InP and GaAs wafers, there are two ways to orient the samples before fusion. One is in-phase fusion [8], which is shown in Fig. 1(b), where the [110] axis of the top wafer is perpendicular to the [110] axis of the bottom wafer. This structure is equivalent to that grown by heteroepitaxy. The other one is antiphase fusion which is shown in Fig. 1(a), where the [110] axes of two wafers are parallel. This structure cannot be realized using epitaxial growth techniques. Macroscopically, the lattice structure of antiphase fused material has inversion symmetry at the fusion interface. It is obvious that the push–pull vertical coupler switch requires antiphase fusion so that the applied vertical electrical field induces opposite index change in the two waveguides. Since some of the electrical and optical properties of crystals, as well as their processing characteristics depend on the crystal orientation, wafer fusion gives an extra degree of freedom to fabricate new types of devices. For example, Yoo [9] has used wafer fusion to change the crystal orientation periodically to realize quasi-phase-matched second-harmonic generation (SHG).

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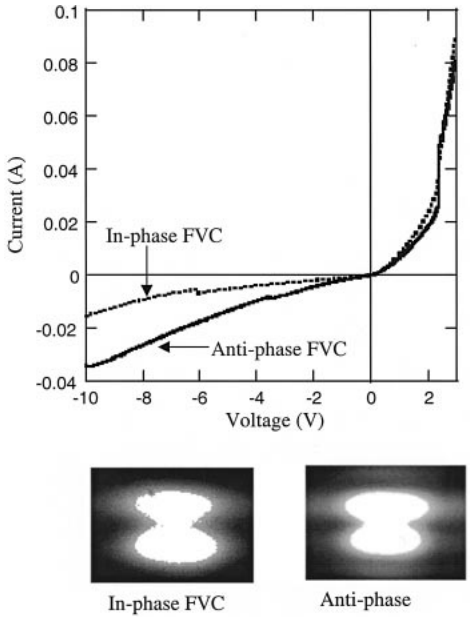

Fig. 2. I–V curves of in-phase and anti-phase FVC's and the electroluminescence images under 80-mA forward current.

In this letter, we study two kinds of FVC's fabricated using in-phase and antiphase fusion. The schematic structure of the devices is shown in Fig. 1, which uses the technology reported in [10] and [11]. Two wafers were grown using metal–organic chemical vapor deposition (MOCVD). For the first wafer, on n+ (001) InP substrate, a 0.5-μm InGaAsP ($\lambda_g = 1.3$ μm) guiding layer, followed by 0.1-μm InP cladding layer, 20-nm InGaAsP ($\lambda_g = 1.15$ μm) etch stop layer and 0.4-μm InP coupling layer were grown. All layers were undoped. The second wafer was grown on p+ (001) InP substrate. It consists of 0.2-μm p+ InGaAs layer, followed by 2 μm p (5×10^{17}/cm^3) InP layer and the same intrinsic InGaAsP and InP layers as the first wafer. The last 190 nm of the bottom 2-μm InP layer was undoped to avoid Zn diffusion to the quaternary layer during the end of the growth and wafer fusion. The 0.2-μm p+ InGaAs layer was used as an etch stop layer to remove the substrate. The device fabrication starts by cleaving two approximately 8×12 mm^2 samples from each of the grown wafers. The top 0.4-μm InP layer of p+ samples is removed. On n+ samples, a ridge waveguide structure with 2–3-μm width along the [110] direction is formed using standard photolithography and selective wet etching techniques. The [110] direction was chosen since HCl etchant produces straight side walls in this direction. The n+ and p+ samples are then fused together at a temperature of 630 °C in a hydrogen atmosphere for 50 min. In one case (fused sample A), the p+ sample was oriented so that its [110] direction was parallel to the waveguides on n+ substrate (i.e., antiphase fusion). For fused sample B, the orientation of the p+ sample was chosen to get the in-phase fusion. After fusion, p+ InP substrates for both samples are removed using HCl etching. Standard ohmic contacts were formed on both sides of the wafers to be able to apply a bias. Fig. 1 shows the stain etched scanning electron microscope (SEM) pictures for both antiphase (A) and in-phase (B) FVC's.

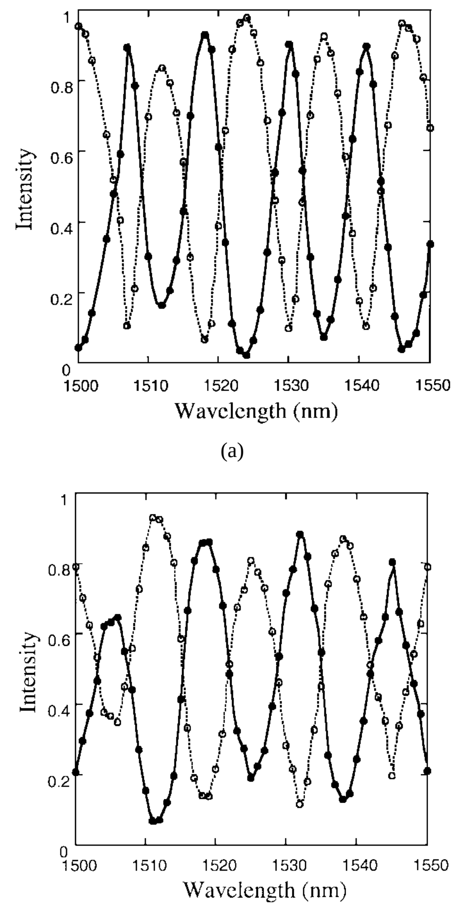

Fig. 3. The light intensity at the output of upper (solid line) and lower (dash line) waveguides of (a) antiphase, (b) in-phase FVC's as a function of wavelength.

Fig. 2 shows the current versus voltage (I–V) curves of the samples A and B. The device size is about 7 mm $\times$ 3 μm. There is a small forward voltage drop of 1 V at the fusion interface. The leakage current of sample A at reverse biases is a little higher than that of sample B. Under forward bias, the luminescence images of anti- and in-phase fused devices are found to be similar as it can be seen in Fig. 2.

To characterize FVC's, a tunable laser source is used to input TE-polarized light through a lensed single-mode fiber (SMF). The image at the output of coupler facet is recorded with an IR camera with an 80$\times$ objective. The samples are mounted to a temperature stabilized stage. First, the passive switching of the two FVC structures was characterized by changing the input wavelength. In response, the effective coupling length changes and the output light switches between upper and lower waveguides (Fig. 3). The oscillation period is a function of the coupling strength between two waveguides and the total length of the couplers. The difference in the measured oscillation period of sample A (11 nm) and sample B (13 nm) matches very well with the different length of the couplers (sample A: 6.9 mm long, sample B: 5.9 mm long). This shows that samples A and B have the same coupling length. Because of the variation in amplitude, the half period looks different at different wavelength (the "eye"

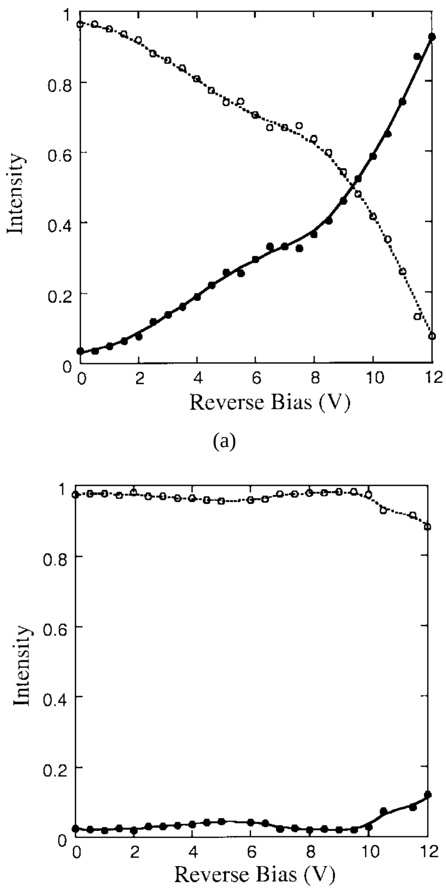

Fig. 4. The light intensity at the output of upper (solid line) and lower (dashed line) waveguides of (a) antiphase and (b) in-phase FVC's as a function of reverse bias voltage.

is big or small), but the actual oscillation period measured from a distance between consecutive minimums is within our experimental resolution (± 1 nm). Then a reverse bias is applied to both samples. The normalized intensities at the output of upper and lower waveguides as a function of bias voltage are shown in Fig. 4(a) (sample A) and (b) (sample B). The antiphase FVC switches at a bias of 12 V while no switching is observed for in-phase fused sample B.

It is known that the mechanisms of index change in p-i-n structures include the linear electrooptic (LEO) effect, the quadratic electrooptic (QEO) effect and the free-carrier effect due to the modulation of the depletion layer. In the current structure, because of a thick 1.6-μm intrinsic layer and because the operation wavelength is far away from the bandgap, the QEO and free-carrier effects are very weak. Furthermore, QEO and free-carrier effects should be the same for both samples, because they are independent of the crystal orientation. Therefore, the LEO effect dominates in current FVC structures. The switching in sample A is because of the push–pull configuration which comes from the inverted crystal orientation. In sample B, the index change in top and bottom waveguides is the same, so the switching requires a much higher voltage.

In conclusion, a push–pull fused vertical coupler switch with crystal inversion symmetry has been demonstrated. Switching under 12-V reverse bias is observed for antiphase FVC's while there is no switching for in-phase FVC's. The wafer fusion technique simplifies the complicate electrode configuration in conventional push–pull type couplers. Additionally, other novel devices can be realized using different crystal structures integrated together.

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