Efficient deeply etched InP/InGaAsP phase shifters with low dark current

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We present fabrication and measurement results of deeply etched InP/InGaAsP waveguide phase shifters. The switching voltages (V_π) of a 2 mm long phase shifter are 4.2 V for TE polarization and 5.2 V for TM polarization. The transmission loss of the 2 μm wide deeply etched phase shifters is about 7 dB/cm for both polarizations. The phase shifters showed very low dark current, on average less than 350 nA at -15 V for the waveguides with less than 2 μm width. At higher voltages the dark current of the deeply etched phase shifters is even lower than that of shallowly etched shifters fabrated from the same wafer.

Introduction

In the last decades, phase shifters based on the electro-optic effects have been heavily investigated. In these devices, different waveguide geometries, shallowly or deeply etched, have been used for various reasons. The shallowly etched waveguide phase shifter was prefered because of the lower transmission loss, and lower dark current at low reverse bias voltage. The deeply etched waveguide phase shifter was used because of the lower capacitance and lower RF transmission loss[1] and smaller bending radius[2]. In this paper, deeply etched narrow waveguide phase shifters based on a P-n-n-N InP/InGaAsP structure, ranging in width from 1 μm to 3.2 μm, have been fabricated and characterized, and the measurement results show very efficient phase shifting, up to $21^\circ/(\mathrm{V}\cdot\mathrm{mm})$ for TE and $17^\circ/(\mathrm{V}\cdot\mathrm{mm})$ for TM, comparable with the shallowly etched phase shifters. The switching efficiency will not change when the waveguide is wider than 2 μm, and decreases when the waveguide gets narrower than 2 μm for TE polarization. The transmission loss of a 2 μm wide waveguide phase shifter is about 7 dB/cm for both TE and TM polarization. The efficiency-loss ratio, $30^\circ/(\mathrm{V}\cdot\mathrm{dB})$, is much higher than that for the one claiming to be the most efficient phase shifter to date[3], which is deeply etched as well but with 3 μm width, $7.7^\circ/(\mathrm{V}\cdot\mathrm{dB})$. Furthermore, these deeply etched waveguide phase shifters showed very low dark current, less then 350 nA at -15 V, which is even better than the shallowly etched waveguide phase shifters fabricated at the same time with the same material.

Fabrication and characterization

The phase shifters are based on the layer stack shown in table 1. The film layer is 500 nm to ensure single mode operation in the transverse direction, and it is n-doped with $6\times10^{16}/\mathrm{cm}^3$. Above the film, the InP cladding layer was also n-doped with the same level based on a trade-off between transmission loss and switching efficiency. During the growth, p-dopant Zinc (Zn) will diffuse from the p-InP into the n-InP cladding layer, which will relocate the pn-junction closer to the film, and result in higher free carrier absorption. The diffusion depth is dependent on the doping level of the n-InP cladding layer[4, 5, 6]. By increasing the level of doping of the n-InP cladding, the pn-junction will

P-InGaAs	$1.5\times10^{19}/\mathrm{cm}^3$	300 nm
p-InP	$5\times10^{17}/\mathrm{cm}^3$	1300 nm
n-InP cladding	$6\times10^{16}/\mathrm{cm}^3$	200 nm
n-InGaAsP	$6\times10^{16}/\mathrm{cm}^3$	500 nm
N-InP	Substrate	Substrate

Table 1: Layer stack of the waveguide phase shifters.

be located more above the film, and consequently, the transmission loss will be reduced. On the other hand, if the pn-junction is closer to the film, the depletion region, where the electric field is highest, will overlap more with the optical field, so that the switching efficiency will increase. Based on our simulations, the thickness of the n-InP cladding layer was chosen to be 200 nm to minimize the waveguide transmission loss, while keeping a relatively high efficiency. The thickness of p-InP was 1300 nm so that the highly absorbing InGaAs contact layer is sufficiently far from the light to prevent additional absorption.

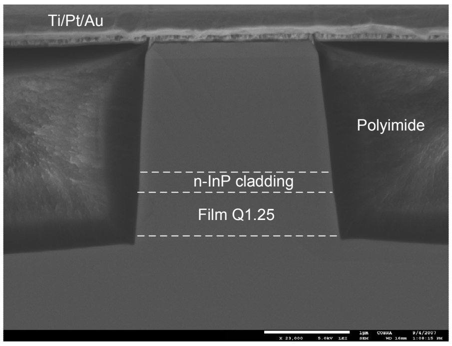

Figure 1: SEM image of a 2 μm wide deeply etched waveguide phase shifter.

The deeply etched waveguide phase shifters range in width from 1 μm to 3.2 μm, and five identical waveguide phase shifters for each width have been designed next to each other. The material was grown on an N-type InP substrate by low pressure metal-organic-vapor-phase epitaxy (MOVPE) at 625 °C. All the phase shifters were etched through the film layer by reactive ion etching (figure 1). Polyimide was spun for passivation and planarization. To obtain good passivation, the polyimide has been baked up to 300°C for one hour in the vaccum oven. From figure 1, we can see that the polyimide adheres very well to the waveguide side wall, and the waveguide width deviation during the fabrication is within $\pm0.1\mu$m. After etching back the polyimide, a 300 nm Ti/Pt/Au metal was evaporated on the p-InGaAs contact layer to form the p-electrodes on the top of the waveguides and the same metalization was provided on the n-InP sample backside. Finally, we cleaved 2 mm long devices for characterisation.

The dark currents of deeply and shallowly etched phase shifters, fabricated from the same material, are shown in fig. 2(left). Both shallowly etched and deeply etched phase shifters have very low dark current at low reverse bias voltage, which indicates the good surface passivation of the polyimide. Surprisingly, at higher reverse bias the deeply etched phase shifters showed lower dark currents than the shallowly etched shifters. We believe that this is due to the surface leakage current that increases more rapidly than the bulk dark current[7], mostly for the shallowly etched phase shifters, which have much larger exposed surface area than the deeply etched phase shifters.

In addition, we see two different trends in fig. 2(left): at higher reverse bias voltage, the dark currents of the shallowly etched phase shifters decrease with waveguide width, while the dark currents of the deeply etched phase shifters increase with width (see also fig. 2(right)). We attribute this to the surface leakage current as well. The narrower shallowly etched phase shifters have more surface exposed to the electrical field than the wider shallowly etched phase shifters, thus they have more surface leakage current. However,

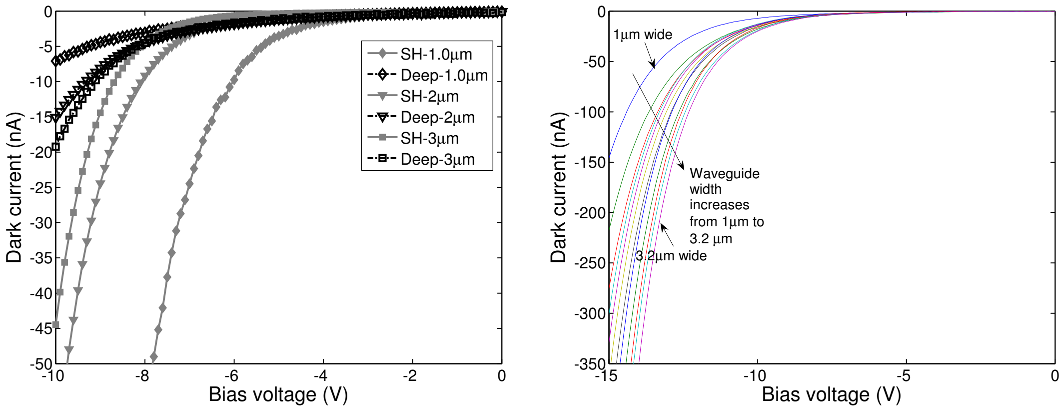

Figure 2: (left) Measured dark currents for deeply etched and shallowly etched phase shifters for different waveguide width. (right) Measured dark currents for deeply etched phase shifter dark currents for different waveguide width.

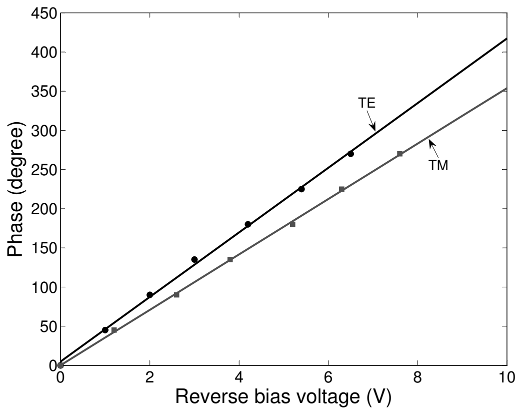

Figure 3: Phase shift as a function of the reversely biased voltage for 2 μm wide, 2 mm long deeply etched waveguide phase shifter.

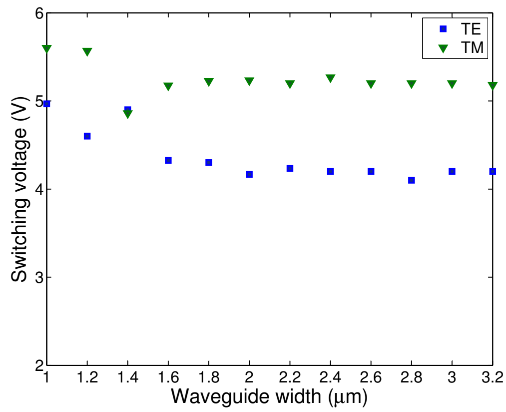

Figure 4: Average switching voltage of five identical 2 mm long deeply etched phase shifters at each width.

the deeply etched phase shifters have the same surface area for all the widths. The difference in the dark current for the deeply etched phase shifters comes from the bulk dark current, which is proportional to the crosssection of the depletion region[8].

To measure the phase shifting efficiency of these deeply etched phase shifters, an erbium doped fiber amplifier (EDFA) was used as a broadband light source. The light was coupled into the waveguide via a microscope objective. Due to reflections at the two cleaved facets, Fabry-Perot fringes will be added to the transmission spectrum. When applying a voltage over the contacts on the waveguides, the fringes will shift according to the phase change in the waveguide. The recorded phase change for 2 mm long, 2 μm wide waveguide phase shifters as a function of the voltage is shown in fig. 3, which shows that the switching efficiency is about $21^\circ/(\mathrm{V}\cdot\mathrm{mm})$ for TE and $17^\circ/(\mathrm{V}\cdot\mathrm{mm})$ for TM. The measured switching voltages (V_π) for the waveguides with different widths are given in fig. 4, and the measurement has been done for all five waveguide phase shifters for each width. The switching voltage will slightly increase for TE polarization when the waveguide width decreases below 2 μm width, due to the reducing overlap of the optical field and the electrical field. However, for TM polarization, it seems that designed 1.4 μm width is the optimum for the overlap of the optical field and the electrical field.

Conclusions

In this paper, the design, fabrication and characterisation of a number of efficient deeply etched narrow waveguide phase shifters was presented. The phase shifting efficiency is measured to be about $21^\circ/(\mathrm{V}\cdot\mathrm{mm})$ for TE and $17^\circ/(\mathrm{V}\cdot\mathrm{mm})$ for TM for a phase shifter width of more than 2 μm. The good polyimide passivation makes it possible for these phase shifter to work at voltages below -15 V with less than 350 nA dark current.

This work is partly funded by the Dutch National Broadband Photonics Access project.

References

[1] J. den Besten, *Integration of Multiwavelength Lasers with Fast Electro-Optical Modulators*. PhD thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2004. ISBN 90-386-1643-0.

[2] D. Maat, *InP-based integrated MZI switches for optical communications*. PhD thesis, Delft University of Technology, Delft, The Netherlands, 2001. ISBN 90-9014700-4.

[3] H. Park, J. Yi, Y. Byun, S. Lee, S. Kim, M. Takenaka, and Y. Nakano, "Investigation of the modulation efficiency of InGaAsP/InP ridge waveguide phase modulators at 1.55 μm," *Jpn. J. Appl. Phys.*, vol. 42, no. 7A, pp. 4378–4382, 2003.

[4] C. Blaauw, F. Shepherd, and D. Eger, "Secondary ion mass spectrometry and electrical characterization of Zn diffusion in n-type InP," *J. Appl. Phys.*, vol. 66, pp. 605–610, July 1989.

[5] V. Swaminathan, C. Reynolds Jr, and M. Geva, "Effect of Zn on the electro-optical characteristics of metalorganic chemical vapor deposition grown 1.3 μm InGaAsP/InP lasers," *Electron. Lett.*, vol. 32, pp. 661–662, Mar. 1996.

[6] M. Camargo Silva, J. Zucker, L. Carrion, C. Joyner, and A. Dentai, "Growth optimization for p-n junction placement in the integration of heterojunction bipolar transistors and quantum well modulators on InP," *IEEE J. Sel. Topics in Quantum Electron.*, vol. 6, pp. 26–30, Jan./Feb. 2000.

[7] K. Linga, H. Olsen, V. Ban, A. Joshi, and W. Kosonocky, "Dark current analysis and characterization of $In_xGa_{1-x}As/InAs_yP_{1-y}$ graded photodiodes with x>0.53 for response to longer wavelengths (>1.7μm)," *J. Lightwave Technol.*, vol. 10, pp. 1050–1055, Aug. 1992.

[8] S. Forrest, "Performance of $In_xGa_{1-x}As_yP_{1-y}$ photodiodes with dark current limited by diffusion, generation recombination and tunneling," *IEEE J. Quantum Electron.*, vol. 17, pp. 217–226, Feb. 1981.