Ferromagnetic-metal-based InGaAs(P)/InP optical waveguide isolator : electrical and magneto-optical characterisation

Mathias Vanwolleghem (1), Wouter Van Parys (1), Steven Verstuyft (1), Roel Wirix-Speetjens (2), Liesbet Lagae (2), Jo De Boeck (2) and Roel Baets (1)

(1) Department of Information Technology (INTEC), Faculty of Applied Sciences, Ghent University, St-Pietersnieuwstraat 41, B-9000 Gent, Belgium, Tel: (+32) 9 264 33 24, mvanwol@intec.rug.ac.be

(2) Interuniversitair Micro-Elektronica Centrum, IMEC vzw, Leuven

Abstract

Transversely magnetised ferromagnetic metallic contact layers, sputtered on top of InP-based semiconductor optical amplifiers (SOA's) enable the monolithic integration of non-reciprocal functions (e.g. isolation) with active InP-based PIC's. We report here on the use of CoFe alloys as ferromagnetic contact layer. The suitability of these alloys for the proposed novel design of an integrated waveguide isolator is validated by magneto-optical parameter extraction measurements based on Magneto-Optical Kerr Effect ellipsometry (MOKE) and electrical contact resistivity measurements, based on the (Extended) Transmission Line Model (ETLM).

Introduction

Progress in optical communication systems requires an ever increasing level of integration of different optical elements into complex photonic integrated circuits (PIC's). Whereas heterogeneous integration techniques allow for separate optimisation of the building blocks of the integrated circuit and fast characterisation of the performance of the circuit, they cannot compete with monolithic integration schemes when it comes to suitability for mass production, stability, yield, scalability and cost reduction.

Non-reciprocal optical components, such as optical isolators and circulators, which meet the requirements of modern telecom systems are up till now not available in an integratable layout. Optical isolators are important because of their stabilising and protecting properties for semiconductor active components such as semiconductor optical amplifiers (SOA's) and laser diodes (LD's). Several types of waveguide optical isolators were successfully demonstrated using magnetic garnet films epitaxially grown on oxide substrates [1,2]. Attempts have been made to integrate these garnet-based waveguide isolators with InP-based laser diodes by direct wafer bonding on InP substrates. However, obtained isolation values of this heterogeneous integration technique have up till now remained limited. Three years ago a novel concept for monolithic integration of non-reciprocity in InP-based PIC's has been proposed [3]. We report here on some of the important experimental aspects of this novel concept.

Concept

An InP-based semiconductor optical amplifier (SOA) with a magnetised ferromagnetic contact close (400nm-600nm) to the active core layer (Fig. 1) exhibits a non-reciprocal behaviour for propagating TM waveguide modes. This is due to the difference in reflection coefficient at the transversely magnetised metal contact for the forward and backward propagating TM waves. This effect is known as the transverse magneto-optic (MO) Kerr effect and, in a waveguide configuration, leads to direction-dependent dispersion equations for the guided TM modes. Due to this modal non-reciprocity, forward and backward propagating modes suffer different optical absorption and by also using the magnetic metal as an electric contact for the underlying SOA structure the residual loss in the forward direction can be compensated. In this way the device remains lossy in the backward direction while it behaves transparently in the forward direction. This allows for the monolithic integration of an isolator with a laser diode, since the SOA and the LD can have the same epitaxial layer structure.
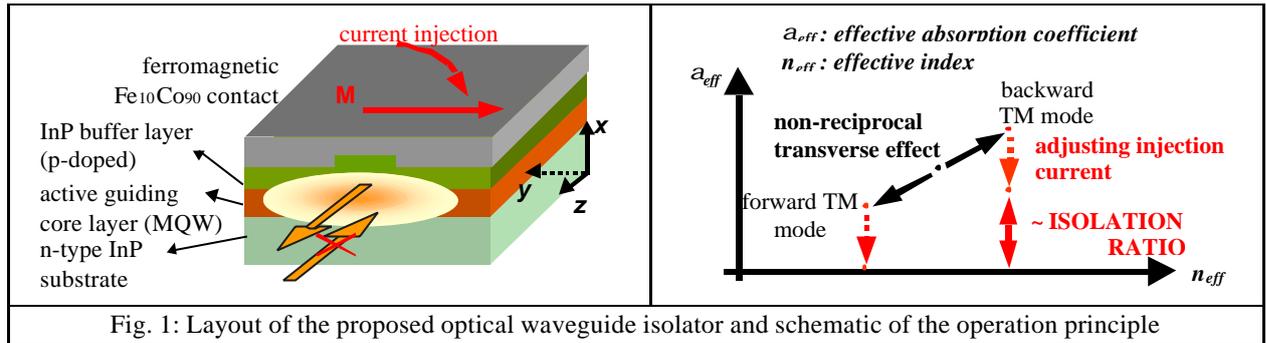
Fig. 1: Layout of the proposed optical waveguide isolator and schematic of the operation principle

In essence the proposed effect is caused, like all magneto-optic effects, by the presence of antisymmetric off-diagonal elements in the dielectric constant of the magnetic metal, as follows:

$$\overset{=}{e} = N^2 \begin{pmatrix} 1 & 0 & -iQ \\ 0 & 1 & 0 \\ iQ & 0 & 1 \end{pmatrix}$$

In this tensor N is the complex refractive index of the metal and Q the so-called (complex) magneto-optic Voigt parameter. The effect of the off-diagonal magneto-optic contribution on the dispersion relation can either be calculated via a first order perturbation scheme or can be taken rigorously into account in ab initio waveguide calculations. We have shown that for common values of Q the difference between both approaches is lower than 5%. This confirms the accuracy of the values we have reported previously. In [4] we reported perturbation calculations for the isolation ratio with values in the range of 20-25 dB for achievable material gains in the active Quantum Well layers of the SOA, and for device lengths of less than 5 mm.

It is clear that the success of the above concept relies heavily on the following key aspects: the achievement of sufficient TM modal gain in the SOA for forward residual loss compensation, the metal/semiconductor interface behaviour in terms of magnetic properties, the Ohmic behaviour of the ferromagnetic metal/semiconductor interface, and the magneto-optic strength (or equivalently the Q value) of the considered ferromagnetic metals for the wavelengths of interest. We report here preliminary experimental results for the latter two aspects.

Ohmic behaviour and contact resistivity of CoFe alloys on p^{++} - InGaAs(P) layers

CoFe has been chosen as the magneto-optic contact material for the device, since, of all the transition metals and their alloys, it is known to have the strongest magneto-optic effects [5].
Three wafers for contact resistivity measurements of CoFe/InGaAs(P) have been grown by MOVPE on semi-insulating InP substrates. They differed only in the top high p-doped contact layer as shown in Table 1. In standard III-V technology p^{++} ternary $In_{0.53}Ga_{0.47}As$ alloys are used as contact layer. This is mainly because of the fact that it is the lowest bandgap alloy in the InP material system. However, for the operating wavelength of the considered device (1.3 *m*m) this low bandgap also gives rise to huge optical absorption. Our simulations predict a drastic reduction in device performance for these levels of optical absorption. This is easily explained by the strong reduction in light intensity near the semiconductor/metal interface, leading to a reduced magneto-optic effect. This motivates the use of a transparent quaternary lattice matched p^{++} InGaAsP contact layer (with a bandgap *l* of 1.17 *m*m) as a possible alternative.

Sample	function	alloy	λ bandgap (μm)	thickness (nm)	dopant	concentration (1/cm^3)
1	buffer	InP		100	nid	
	contact	GaInAs	1.65	100	Be	2.60E+19
2	buffer	InP		100	nid	
	contact	GaInAsP	1,17	100	Be	1.90E+19
3	buffer	InP		100	nid	
	contact	GaInAsP	1,17	50	Be	1.90E+19
Table 1: layer structures of the TLM test samples						

For all three samples suitable TLM patterns have been defined, with a thickness of 50 nm for the sputter-deposited $Co_{90}Fe_{10}$ metal stripes. Additionally, Schottky diodes have been processed to perform I-V contact measurements. The I-V curves have been measured for the contacts as-deposited and for three different rapid thermal annealing steps. Traditionally, it is expected that annealing lowers the contact resisitivity. However, it still has to be investigated if these annealing procedures cause a possible degradation of the magnetic properties of the interface, such as the formation of a magnetic dead layer. Such a layer can be seen as a thin highly absorptive metallic layer which has lost its magnetic (and hence its magneto-optic) properties. It is clear that this kills the device behaviour in much the same way as an absorptive contact layer does. These dead layer investigations are underway.

Figure 2 shows the results of the I-V measurements. The as-deposited CoFe/InGaAs contacts show very good Ohmic behaviour. Thermal annealing improves these contacts only slightly (with an optimal annealing temperature around 350°C). The as-deposited quaternary-based contacts are clearly worse, but an annealing step drastically improves their behaviour. There has been no observed degradation in morphology for annealing temperatures up to 450°C.
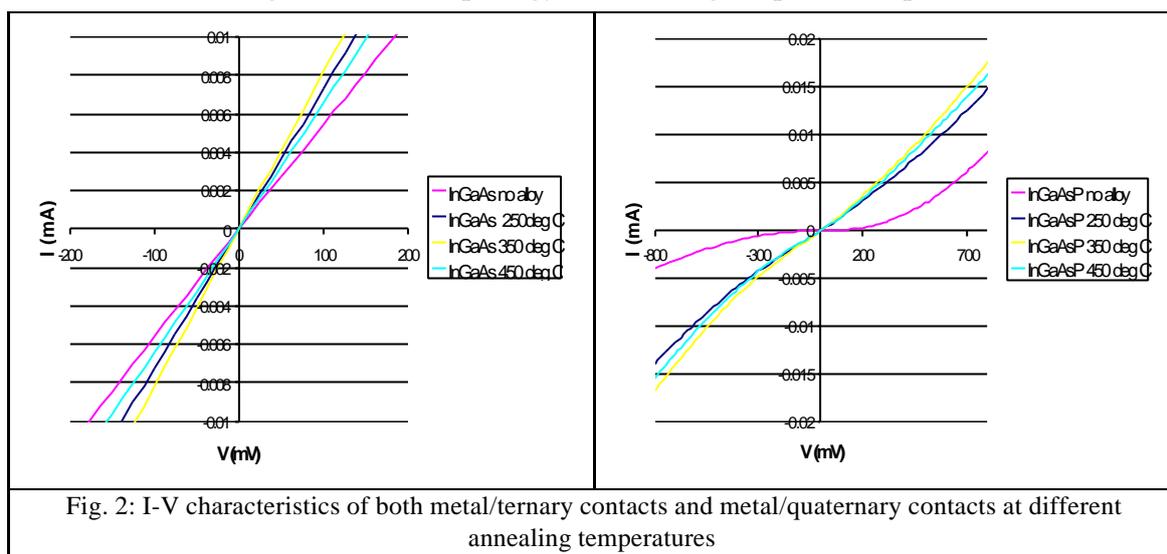

Fig. 2: I-V characteristics of both metal/ternary contacts and metal/quaternary contacts at different annealing temperatures

TLM contact resistivity extraction measurements for the as-deposited contacts have been performed. For the alloyed contacts these measurements are underway. The results are summarised in Table 2. The values for the ternary/CoFe contacts are compatible with standard Ti/Au or Ti/Pt contacts [6]. Those for the quaternary/CoFe contacts are expected to be as good after Rapid Thermal Processing (RTP) at 200°C or even less.

r (Ω*cm^2)	InGaAs	InGaAsP
TLM	8.247E-05	4.983E-04
ETLM	2.741E-05	9.567E-04

Table 2: contact resistivity of as-deposited contacts. ETLM is a refined TLM model, taking current crowding into account

Magnetooptic Kerr effect (MOKE) based material characterisation

The magnetooptic strength of a ferromagnetic metal is characterised by its complex Voigt parameter Q. Up till now this parameter has only been measured with limited accuracy for near IR wavelengths [7]. Several Q-extraction methods are known in literature, all of them rely on the magneto-optic Kerr effect. The MO Kerr effect causes a change in polarisation state when pure s- or p-polarised light is reflected off a magnetised sample. Thus, MO parameter extraction is a generalised version of optical ellipsometry. We have extended an existing MOKE setup with a method for IR Q-parameter extraction which does not require scanning of the incidence angle as in normal ellipsometry [8], making the setup more compact. Only two rotatable polarisers are required. The method is based on the measurement of the fractional intensity

change upon magnetisation reversal in the sample and this for a range of analyser angles. It can be proven that resonance-like curves will be obtained. Combined with a least-squares fitting method and a software tool to simulate the reflection of polarised light off a MO multilayer stack, this method can be used to determine both the magneto-optic and optical constants of the CoFe alloys, and the direction of the magnetization in the sample. Fig. 3 illustrates this measurement technique. We have checked its feasibility for visible light and have found values in agreement with values in literature. Extraction measurements for 1.3 μm light are underway and will be reported.
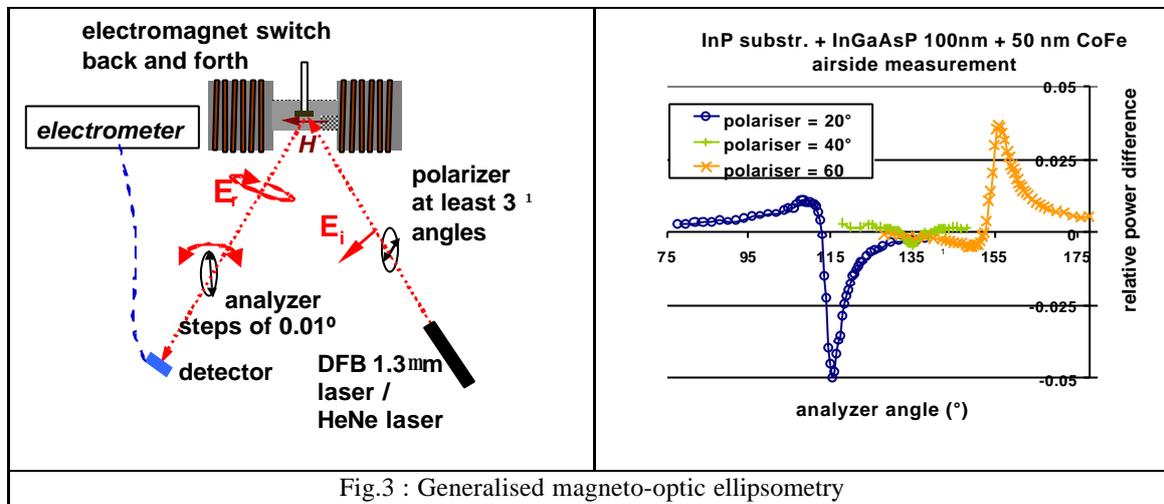

Fig.3 : Generalised magneto-optic ellipsometry

Furthermore this measurement technique can also be used to detect the presence of a possible magnetic dead layer at the CoFe/semiconductor interface, by measuring the Kerr effect through the substrate. This experiment will be used to complement results from other magnetic dead layer measurements.

Conclusion

We have reported characterisation techniques and results on two crucial aspects of the novel type of integrated optical waveguide isolator. A $Co_{90}Fe_{10}$ alloy has been proven to show good Ohmic behaviour when sputtered on p^{++}-InGaAs(P) layers, though thermal annealing might be necessary. Rough knowledge of the Q parameter of pure Co at 1.3 μm confirms the predicted theoretical device performance. Precise magneto-optical characterisation of this alloy in the near IR is underway.

Acknowledgements

References

[1]   Fujita J et al., 'Polarization-independent waveguide optical isolator based on nonreciprocal phase shift ", *IEEE Photon. Technol. Lett.,* Vol.12, pp. 1510-1512, 2000.

[2]   Yokoi H et al., "Demonstration of an optical isolator by use of a nonreciprocal phase shift ", *Appl. Opt,* Vol. 38, pp. 7409-7413, 1999.

[3]   M. Takenaka et al., "Proposal of a Novel Semiconductor Optical Waveguide Isolator", *Proc. of 11th Intern. Conf. on Indium Phosphide and related materials*, 1999, pp.289-292.

[4]   M. Vanwolleghem et al.,"Ferromagnetic-metal-based InGaAs(P)/InP optical waveguide isolator : steps towards experimental validation", *Proc. of IEEE Annual Meeting*, 2001, pp.

[5]   A.K. Zvezdin and V.A. Kotov, Modern Magnetooptics and magnetooptical materials, Institute of Physics Publishing, 1997, ch. 10, pp.201-211

[6]   A. Katz et al, "Pt/Ti/p-In0.53Ga0.47As Low-resistance nonalloyed Ohmic contact formed by rapid thermal processing", *Appl. Phys. Lett.*, Vol. 54, pp. 2306-2308, 1989.

[7]   G.S. Krinchik and V.A. Artem'ev, "Magneto-optical properties of Ni, Co, and Fe in the ultraviolet, visible and infrared parts of the spectrum", *Soviet Physics JETP*, Vol. 26, pp. 1080-1085, 1968.

[8]   Berger A and Pufall MR, " Generalized magneto-optical ellipsometry", *Appl. Phys. Lett.*, Vol. 71, pp. 965-967, 1997.