Yield Improvement by Wafer Mapping the Polarization Correction in InP/InGaAsP WDM Optical Power Monitors

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Keywords: INP, INGAASP, OPTICAL POWER MONITOR, WDM, PL, XRD

Abstract

We describe how a careful analysis of Photo-Luminescence, Mis-Match and Thicknesses in epitaxial layers that form the passive optical waveguide of a fully integrated Optical Power Monitor, can be used to eliminate yield losses from polarization dependant frequency shifts. The element which corrects polarization shifts, the compensator, is a prism like feature etched into a key epitaxial layer. Its shape can be adjusted for different dies according to the radial distributions found in the epitaxial layers from PL and X-ray mis-match maps. Yield losses from polarization dependant shifts are decreased from 90% to practically ~0%.

INTRODUCTION

InP based photonic integrated circuits for Wavelength DeMultiplexing (WDM) applications are fabricated from single growth epitaxial wafers. In this technology, WDM is achieved by etching a small dispersive echelle grating (~2mm) through the passive wave-guiding section. The individual wavelengths are then re-collected by single mode waveguides etched at the appropriate positions on the dies. The integration of an increasing number of channels depends in part, on the ability to grow epitaxial layers that meet design specifications and tolerances. This is especially critical for the WDM part of the devices because light impinging on and reflected from the echelle grating, travels through a two dimensional planar or slab waveguide where tight control of the effective index of refraction is required to avoid centre frequency offsets and Polarization Dependent Frequency (PDF) effects. The physical parameters, which determine the effective index of refraction of the slab waveguide, are the composition, lattice mismatch and thickness of the quaternary InGaAsP core layer as well as the thickness of the InP cladding layers. In this work we explain how a competitive edge is gained in the manufacturing of 7mm x 20mm, 44 Channels, 100GHz, Optical Power Monitors (OPM) fabricated on 4" InP wafers, by making small fabrication adjustments to compensate for unavoidable small variations in the effective index of refraction of the epitaxial wafers.

The composition and mismatch of the quaternary optical core layer is obtained from Photo-Luminescence (PL) and X-Ray Diffraction (XRD) data respectively. A model is used to calculate the refractive index of the quaternary core material from the PL and XRD data. Electron Microscope imaging of cross-sections of sacrificial wafers are used to obtain precise thicknesses for all layers allowing the calculation of the effective index of refraction of the slab waveguide for both polarizations. In essence, a Map of the effective index of refraction is calculated for each wafer. This thorough analysis of the core layer for each wafer is then used to select the optimized set of PDF "compensating" elements or compensators and wavelength layouts, for a wafer. In practical terms, a wafer map is generated for the I-line stepper job to print specific compensators and associated waveguides on each die from a series of pre-existing sets.

To help simplify this process and to avoid excessive analysis, XRD and PL data of the optical core layer from some wafers were analyzed carefully to reveal existing trends. In particular, a small drop-off of the PL and Mismatch were found near the edge or exclusion zone of the wafers. Drop-off values of ~5 nm in PL and ~ 250 ppm in XRD were consistently seen. These are extremely small but are sufficient to make the difference between a failed and a good device. We will show that fine-tuning the compensator and waveguide selection for near edge regions of the wafer has raised yields by up to 40%. Moreover the ability to adjust the compensating elements to a specific wafer has increased the wafer-to-wafer yield by ~100%. The thickness of the epitaxial layers did not show the same radial dependence. The reproducibility of the radial dependence of PL and XRD from wafer to wafer is such that only one mismatch data point per wafer and one PL and thicknesses set of data point per batch is sufficient to generate the optimized wafer map of compensator sets.

OPTICAL POWER MONITOR: AN OVERVIEW

OPM's are devices that split the different wavelengths or channels used in telecommunications from an optical fiber (de-Multiplexing) and measure the respective intensities in each channel. Our devices operate in the so-called C- and Lbands near λ~1550µm where adjacent wavelengths to separate are different only by 0.8 nm (or 100GHz).

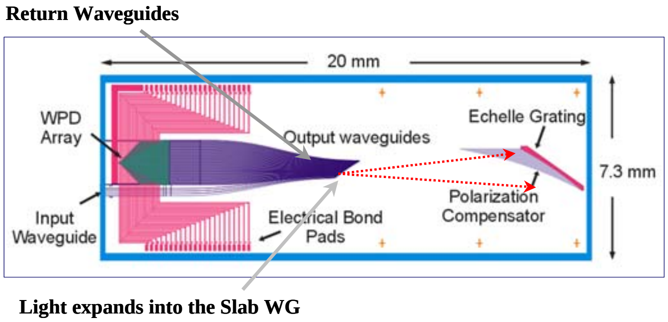

Fig. 1 Magnified View of an OPM die. The dotted lines show light expanding towards the grating. The grating reflects individual wavelengths into separate return waveguides. The length of the die is 2 cm.

Fig. 1 shows an OPM die to illustrate how our device performs de-multiplexing. Light from an optical fiber is launched from the left hand side and travels through a shallow etched waveguide which stops near the middle of the die. At this point, light is allowed to expand towards a grating designed to diffract light backward into shallow individual waveguides located just above the input waveguide. Each one of these waveguides matches a specific wavelength or channel and couples the light into the appropriate detector on the far LHS.

Our OPM devices are fabricated on 4” epitaxial InP wafers. A picture of a finished wafer with 36 OPM dies and test structures is shown in Fig. 2. To minimize epitaxial costs and eliminate re-growths, we use a vertical integration scheme, which requires only a single epitaxial growth run. [1], [2]. In this approach, the first set of epitaxial layers grown are used to make the passive waveguides of the devices while the upper epitaxial layers are used only in the fabrication of the detectors. The discussion in this work will be limited to the passive waveguide section. As explained below, the device specifications are such that only small variations in the index of refraction and thickness in the passive epitaxial layers near the edge of the wafer are sufficient to fail otherwise perfect dies.

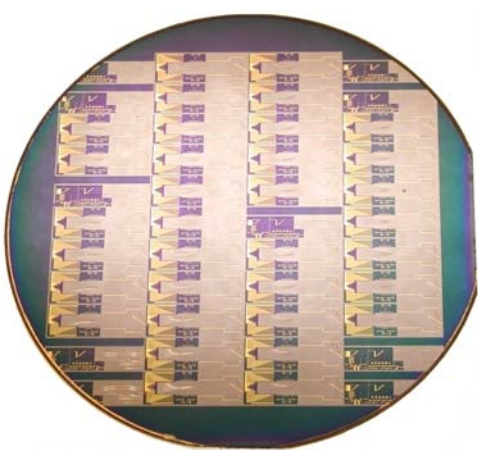

Fig.2 Finished 4” OPM InP based wafer with 36 Product and test dies.

POLARIZATION CORRECTION

One further level of difficulty in optical components is the ability to deal with the arbitrary polarization states of light coupled in from the fiber. The issue is that different states of polarization will propagate differently because the boundary conditions are not the same for the two polarizations. Technically, this means the effective refractive index, n_{eff}, of the waveguide is different for different polarizations or that the waveguide is bi-refringent. This is true in the planar geometry waveguide used in our OPM’s where confinement of the modes normal to the plane is achieved by the epitaxial layers. To solve this issue a polarization compensator is etched before the grating [3]. A cross-section of the polarization compensator is illustrated in Fig. 3 where the shape of the optical modes is drawn. In the compensator region where the top layer of the upper cladding and the etch stop have been removed, the optical modes are pushed downward. The key point here, is that the downward shift also results in a larger value of n_{eff}(TE)-n_{eff}(TM) in going from the slab area to the compensator area and it is sensitive to the core material compositions and the layer thicknesses. With the correct compensator design, it is possible to offset the issue of birefringence and to funnel both TE and TM into the appropriate return waveguides for all wavelengths.

We show below that the fabrication of the compensator itself is made easy by the use of a wet etch stop and that choosing the appropriate compensator design for different regions of a wafer results in a significant yield improvement. The compensator selection and key fabrication steps are described below.

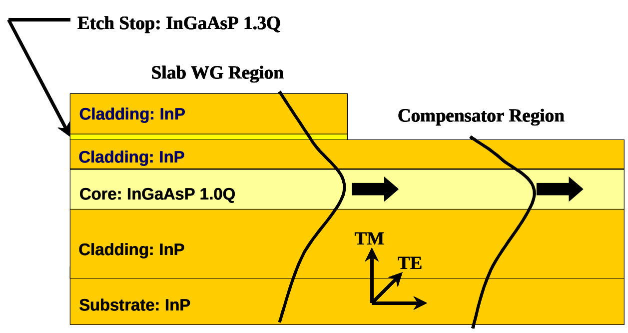

Fig. 3 Optical Mode profiles in the Slab and Compensator regions. The modes are pushed down in the compensator regions. TM and TE Polarizations are shown.

COMPENSATOR MAPPING FROM EPI GROWTH CHARACTERIZATION

The fabrication of the OPM wafers does not start before the full characterization needed for lot acceptance of the epi growth has been done. Three elements are needed to determine the effective refractive indices, which are used to select the appropriate set of compensators: The layers’ thicknesses, the PL and the X-Ray mis-match of the core layer.

The epi layers' thickness is obtained by cleaving a piece from a sacrificial test wafer, performing a dilute sulfuric peroxide delineation etch followed by a FESEM thickness analysis. A picture of a FESEM Cross-section is shown in Fig. 4. By careful calibration of the FESEM we have been able to measure epitaxial layers varying in thickness from 60 nm to 1000 nm to a precision of 1-2% [4]. No significant radial variation in thickness was found on a given wafer and for all practical purposes the layers' thicknesses is assumed constant across our wafers. However, small (≤ 5%) but significant enough variations in thickness for our OPM device were found from growths to growths to be included in the calculation of the n_{eff}'s.

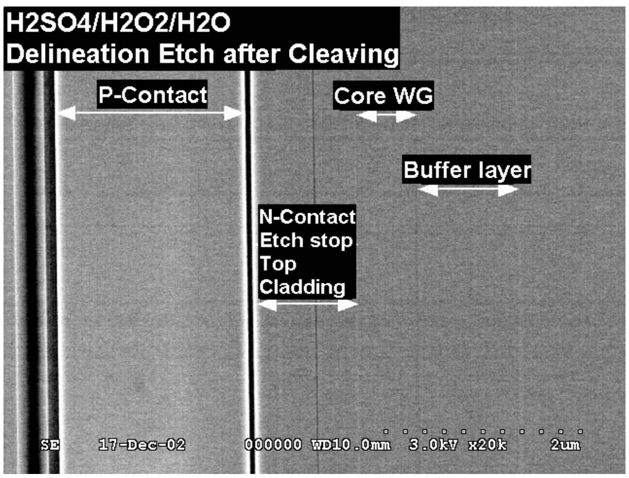

Fig.4 Delineation/FESEM Cross-section used to measure epitaxial layers thicknesses.

The PL of the core layer is obtained from the sacrificial test wafer piece after removing the top layers down to the top cladding layer. This is necessary as no PL scheme has been found to probe through the ~ 2 µm of top epi layers efficiently. The X-Ray mis-match data is obtained on each wafer. Again, we found little variations from wafer-to-wafer from the same run only small but significant variations from growth to growth. The important point however is that a slight radial decrease in both PL and mis-match values was found. More precisely, for any given wafer, the PL and Mis-match remained constant over a radius of about 30 mm but fell continuously from that point on to the exclusion zone of wafer (~45 mm away) by ~ 5nm in PL and 250 ppm in lattice mismatch. We believe this correlation is caused by the difficulty in controlling the small amounts of As, ~8%, in the 1.0Q core layer. The consistent radial changes seen in PL and X-Ray mis-match are used for each single wafer to calculate the compensator map that will give the optimum yield. A typical map obtained from this analysis is shown in Fig. 5. The dotted circle indicates roughly the exclusion zone. The color code and last number in the label (45,50,55) indicate the type of compensator to use. The last number indicates the degree of polarization dependent frequency correction in GHz. Changes in the range of 5-10 GHz in the polarization correction can be seen as the dies approach the edge of the wafers. To give an idea of the magnitude of the change, a 10GHz correction corresponds to an adjustment in the return waveguide position of ~1.3µm, while the specification on the polarization dependent frequency is 5GHz.

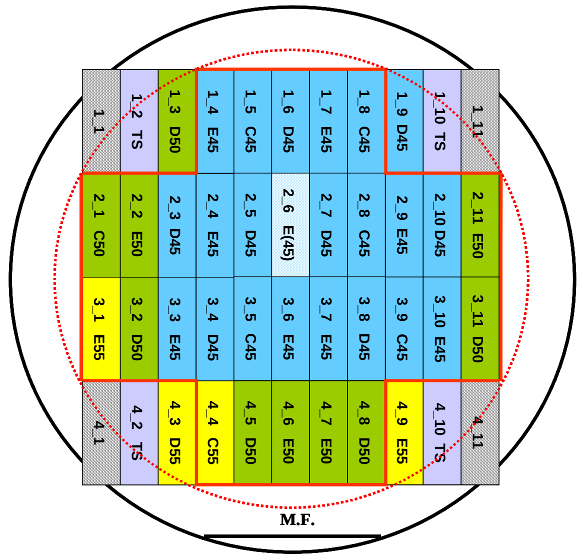

Fig.5 Typical Compensator Map selected for a given wafer after analysis of its PL, Mis-match and epitaxial layer thicknesses.

FABRICATION STEPS AND ISSUES FOR PASSIVE ELEMENTS

Grating

The grating is the diffractive element of our OPM device. It is made of about 400 tiny deep etched mirrors. Fig. 6 shows a close up view of the tiny reflectors. That picture was obtained after removing the Ti/Au metallization on a finished product. The width of the teeth is ~ 3.5 um. The challenges for the fabrication of the grating are uniformity, verticality of the deep etch (± 1°), smoothness of the vertical mirror surfaces (≤ 20nm) and minimum corner rounding. All of the above factors may lead to losses or channel cross talks which affect performance. The grating fabrication is the first step following alignment marks. This is because in optical gratings, uniformity is as important as corner sharpness and the best Photo-Resist (PR) uniformity is obtained at the beginning of the process. Our grating etch process uses a 1.0 um PECVD oxide mask. The oxide mask is etched using a CF_4 + H_2 chemistry in a Trikon ICP-RIE. An I-line PR, Arch(Fuji) OIR 620-09 (~880 nm), and ASML stepper technology is used to define the oxide mask. High selectivity of the oxide mask (InP:SiO_2 30:1) is needed to keep good verticality and smooth walls down to depth of ~6-7um. This high selectivity was achieved using a Cl_2, CH_4, and H_2 chemistry in a RIE-ICP Oxford tool. Sharpness, verticality and smoothness are important at the bottom of the deep etch where the passive layers are found.

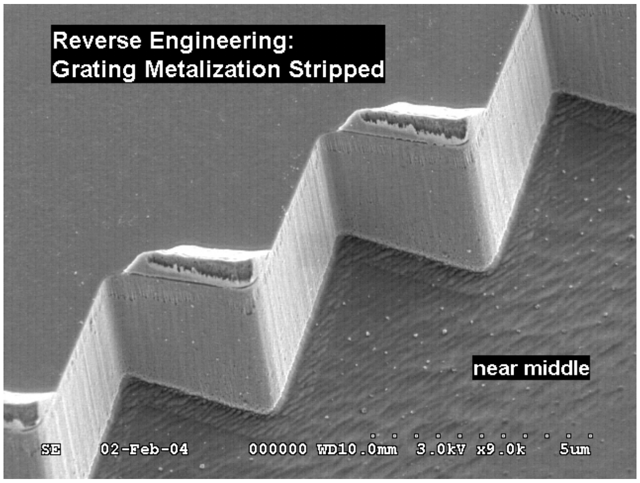

Fig. 6 FESEM Image of an OPM Grating after removal of the metalization.

Compensator & Passive waveguides

Prior to the fabrication of the compensators & waveguides, detectors are made which result in the removal of the top active epitaxial layers. The epitaxial layers, which remain in other areas, are shown in Fig. 3 under the label; Slab waveguide region. The compensator and passive waveguides are then simultaneously fabricated using once again a hard SiO_2 mask but with a CH_4, H_2 based chemistry. The required depth in this case is only ~0.5 um and chlorine is not used here to lower the etch rate and obtain better etch depth control. The compensator and waveguide etch is then finished with a standard $HCl:H_3PO_4$ wet etch ending on the thin (5nm) etch stop (see Fig. 3) resulting in perfectly smooth surfaces. The etch stop must be as thin as possible so that it does not perturb the optical mode propagation. There was some initial concerns with punching through the thin 5nm etch stop but the choice of 1.3Q ($Ga_{0.28}In_{0.72}As_{0.61}P_{0.39}$) has never been found to fail. Smooth surfaces are important for both the compensator and the waveguides since the optical modes interact with these surfaces and roughness would lead to light insertion losses.

YIELD IMPROVEMENTS

The yield improvements obtained by using specific sets of compensator maps for individual wafers is two-fold. First, if only one compensator were to be used in the fabrication of our OPM's the yield loss from PDF shift alone would be 90%. In this case the only way to improve on yield would be to narrow the tolerances on epitaxial growth leading to drastic increases in epitaxial supplier costs. If different compensators could be selected for different wafers but with one type only per wafer, the yield loss from PDF would be 39%. This is directly seen from the map shown in Fig 5 where 22 dies near the middle have the same polarization correction while 14 on the perimeter have different PDF correction or compensator. These 14 dies would be lost if the correct compensator element were not chosen properly.

CONCLUSION

We have shown how in-coming analysis, PL, X-Ray and thicknesses obtained on 4" InP epitaxial wafers can be used to pre-select an appropriate set of compensators or corrective elements fabricated in-line to increase yield losses from PDF issues in the fabrication of fully integrated Optical Power Monitors. Yield losses from polarization issues in our Optical Power Monitors are decreased from 90% to ~0% by generating the appropriate compensator maps before starting the fabrication. These efforts are well justified for these high margin products with ~ 40 dies per wafers.

ACKNOWLEDGEMENTS

The authors would like to thank all MetroPhotonics employees who helped make this part of the OPM project work.

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ACRONYMS

FESEM: Field Emission Scanning Electron Microscope
HBT: Heterojunction Bipolar Transistor
ICP-RIE: Inductively Coupled plasma-Reactive Ion Etching
n_{eff}: effective refractive index
OPM: Optical Power Monitor
PDF: Polarization Dependent Frequency
PECVD: Plasma Enhanced Chemical Vapor Deposition
PL: Photo-Luminescence
WDM: Wavelength DeMultiplexing
XRD: X-Ray Diffraction