WF5 **2:45 PM**

New All 2-inch Manufacturable High Performance Evanescent Coupled Waveguide Photodiodes with Etched Mirrors for 40 Gb/s Optical Receivers

M. Achouche, S. Demiguel, E. Derouin, D. Carpentier, F. Barthe, F. Blache, *Alcatel R&I, Marcoussis, France;* V. Magnin, J. Harari, D. Decoster, *IEMN, Villeneuve d'Ascq, France, Email: mohand.achouche@alcatel.fr.*

Evanescent PIN photodiodes are fabricated using all 2"-InP processing including on-wafer mirrors and coatings. 0.73 A/W responsivity at 1.55 µm, -1 dB vertical coupling tolerance of 2.2 µm and 47 GHz bandwidth are simultaneously demonstrated.

Introduction

Future optical receivers for 40 Gb/s DWDM transmission systems require photodiodes having broad bandwidth, high quantum efficiency, low polarization tolerances and good power handling capabilities. High power characteristics could ensure that optical amplification using Erbium Doped Fiber Amplifiers (EDFA) [1] or Semiconductor Optical Amplifiers (SOA) preamplifiers [2] increase sensitivity before PIN-TIA photoreception.

Evanescent edge-coupled WGPD (Wave-Guide Photo-Diode) have received wide acceptance because one can design independently photodiode structure (bandwidth) and fiber-device coupling (external quantum efficiency). This approach has demonstrated interesting performances [3], [4]. However, the fabrication of a spot size converter require sub-micron lithography and two additional waveguide etching for the realization of the tapers. Our solution uses a planar diluted multimode waveguide without additional, usually costly, AR coating. This approach has been demonstrated for high performance 10 Gb/s optical hybrid-integrated receivers using passive alignment on Si-mother board and flip-chip technology [5]. We do show that the processing simplicity of this design make it suitable for the fabrication of 40 Gb/s low cost receivers and high performance long haul receivers as well.

In this work, evanescent edge-coupled WGPD photodiodes are developed using 2-inch wafer process technology with dry etched mirror facets for on-wafer AR coating. Responsivity of 0.73 A/W with very low polarization dependence and wide coupling tolerances (2.2 µm vertical and 4.1 µm horizontal), bandwidth of 47 GHz and 16 mA photocurrent have been achieved.

Device design and fabrication

The epitaxial structure of the evanescent coupling photodiode shown on Fig. 1 is grown using Gas Source Molecular Beam Epitaxy (GSMBE) on InP-Fe substrate. The structure comprises a nid InGaAs absorption layer inserted between a p+ InP layer and a n+ InGaAsP matching layer. A multimode diluted waveguide made from very thin quaternary layers inserted in InP is used to carry the light from the input facet to the absorber [6]. A matching layer is inserted between the waveguide and the absorber to increase coupling efficiency.

The design of such a structure was performed using a genetic algorithm, a multiparameter optimization method to carry the numerous optimization parameters, coupled to a 2D-BPM simulation tool [7]. Further calculations have then been performed using 3D-BPM to take into account lateral divergence.

Fig.2 shows the measured and simulated responsivity at 1.55 µm wavelength for various optical input waveguide lengths, for a 5x25 µm² area photodiode. The calculated responsivity follows a sinusoidal shape with 55 µm period and reaches a maximum as high as 0.98 A/W for a waveguide length around 18 µm with a polarization dependence below 0.2 dB. The position of the maximum measured responsivity (0.73 A/W) is very close to the theoretical results with similar shape behavior either for TE or TM polarization and as expected TE/TM polarization dependence below 0.1 dB for waveguide length higher than 20 µm. However, slightly lower responsivities are measured on our PIN diodes, probably due to optical loss induced by roughness on the input facet requiring yet more optimized dry etching process.

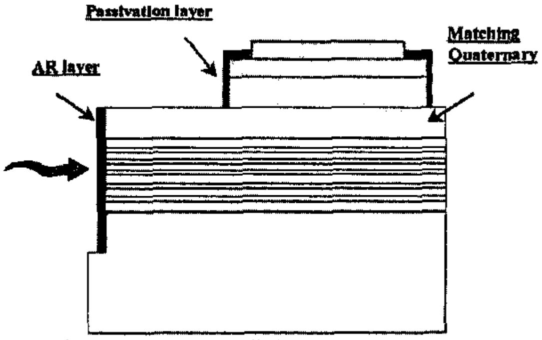

Fig. 1 Schematic view of evanescent PIN photodiode

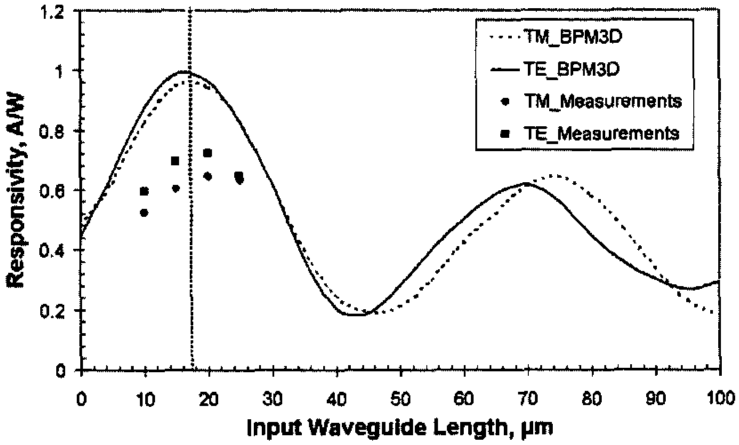

Fig. 2 Responsivity at 1.55 µm wavelength versus optical input waveguide lengths (measurement and simulation)

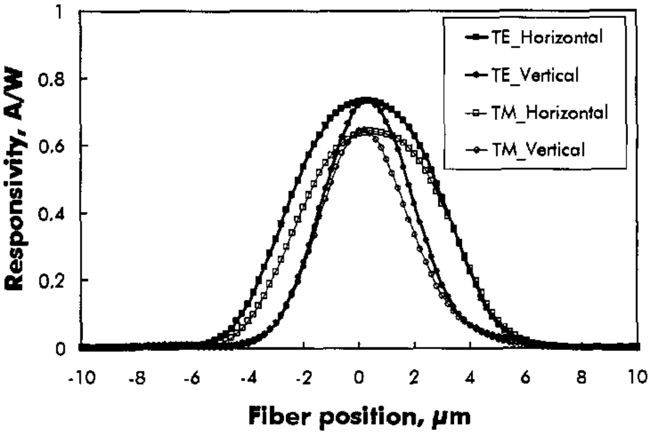

Fig. 3 Responsivity of a 5x25 µm² photodiode with a 20 µm long input waveguide (measurement at 1.55 µm wavelength)

The process flow of our edge-WGPD photodiodes fabrication is mainly based on dry etching process for mesa realization, device isolation and waveguide input facet etching with anti-reflection coating deposition on wafer. V-grooves for high precision cleaving are defined using wet chemical etching.

Typical dark currents are ~ 2 nA at a reverse voltage of 3 V and capacitances of ~ 40 fF (extracted from S11 reflection measurements up to 65 GHz).

Device characteristics

Fig. 3 shows responsivity at 1.55 µm wavelength for a 5x25 µm² photodiode with a 20 µm long input waveguide. The measurements are performed using a XYZ piezoelectric positioner with automatic fiber alignment capability allowing precise alignment of the fiber in front of the photodiode in order to measure the fiber position tolerances. A lensed fiber with 4.2 µm mode diameter is used.

Responsivities are 0.73 A/W and 0.64 A/W for TE and TM polarization, respectively, indicating low polarization dependence (< 0.5 dB). The measured misalignment tolerances at -1 dB are 4.1 µm² and 2.2 µm for the horizontal and vertical directions respectively, which are very close to simulation results.

Fig. 4 shows the frequency response (dBe) of a 5x15 µm² photodiode (0.57 A/W) using an heterodyne setup with optical powers of -10 dBm

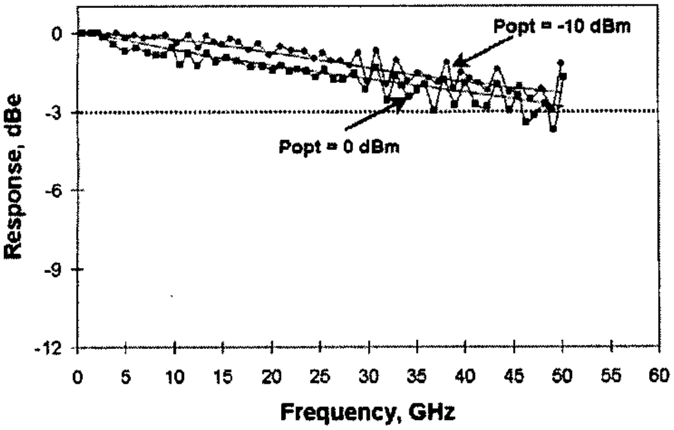

Fig. 4 Frequency response (dBe) of a 5x15 µm² photodiode with optical powers of -10 dBm and 0 dBm on a 50 W load and 2 V reverse bias

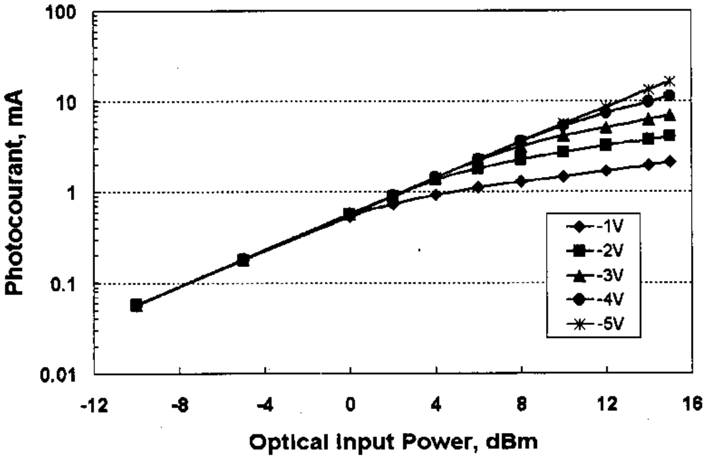

Fig. 5 PIN Photocurrent at 1.55 µm versus optical input power for various reverse bias (1V to 5 V)

and 0 dBm on a 50 W load and a 2 V reverse bias. A -3 dB bandwidth over 50 GHz is obtained at both -10 dBm and 0 dBm optical power. A bandwidth of 47 GHz is achieved on a 5x25 µm² photodiode and even on a 5x30 µm² a 40 GHz bandwidth is measured.

In order to evaluate the robustness of the evanescent PIN photodiodes, photocurrent measurements at 1.55 µm for various optical input power were conducted (Fig. 5). More than 16 mA photocurrent were extracted from the PIN (reverse bias of 5 V) corresponding to an optical input power of 15 dBm demonstrating the good power handling capabilities of such a structure.

Conclusion

We have developed InGaAs evanescent WGPD photodiodes with an original diluted optical waveguide design using a new complete 2-inch wafer processing which includes on-wafer antireflection coating and V-grooves for precise cleaving. The photodiodes exhibit low dark current (~ 2 nA at 3 V reverse bias), responsivities > 0.73 A/W with low polarization dependence and large alignment tolerances. Bandwidths in excess of 50 GHz demonstrate the capability for high speed operation (40 Gb/s) even at high power levels. This performance and simple manufacturing confirm the application potential for low cost and/or high performance 40 Gb/s receivers.

References

[1] S. Kuwahara, K. Yonenaga, Y. Miyamoto, K. Murata, H. Kitabayashi, N. Shimizu, H. Toba, Electronics Letters, Vol. 38 (2002), p. 38.

[2] E. Legros, Th. Barrou, S. Vuye, L. Giraudet, C. Joly, F. Blache, T. Ducellier, M. Goix, Proc. ECOC'98, p. 69.

[3] T. Takeuchi, T. Nakata, K. Makita, M. Yamaguchi, Electronics Letters, Vol. 36 (2000), p. 972.

[4] S. Demiguel, L. Giraudet, P. Pagnod-Rossiaux, E. Boucherez, C. Jany, L. Carpentier, V. Coupe, S. Fock-Yee, J. Decobert, F. Devaux, Electronics Letters, Vol. 37 (2001), p. 516.

[5] M. Achouche, E. Derouin, D. Carpentier, E. Boucherez, P. Pagnod, C. Jany, F. Poingt, S. Grosmaire, V. Coupe, F. Blache, J. Bonnet-Gamard, L. Giraudet, F. Devaux, ECOC'2001, p. 552.

[6] L. Giraudet, J. Harari, V. Magnin, P. Pagnod, E. Boucherez, J. Decobert, J. Bonnet-Gamard, D. Carpentier, C. Jany, F. Blache, D. Decoster, Electronics Letters, Vol. 37 (2001), p. 973.

[7] V. Magnin, L. Giraudet, J. Harari, J. Decobert, P. Pagnod, E. Boucherez, D. Decoster, J. Lightwave Tech., Vol. 20 (2002), p. 477.

WF6 **3:00 PM**

Highly Reliable Wave-Guide Photodiode with Wide Bandwidth of 50 GHz at the Low Operation Voltage of -1.5 V

M. Nakaji, E. Ishimura, Y. Hanamaki, T. Aoyagi, Y. Mitsui, *Mitsubishi Electric Corp., Itami,Hyogo, Japan, Email: nakaji.masaharu@lsi.melco.co.jp.*

Wave-guide photodiodes with 50 GHz bandwidth at the low operation bias voltage of -1.5 V are realized, which have life time over $8x10^7$ h at 25°C by adopting buried structure with semi-insulating InP.

1. Introduction

High-speed optical transmission system over 40 Gbps are required in current and near future. Broad bandwidth and high quantum efficiency PIN photodiodes (PIN-PD) are indispensable in such system, Wave-guide PIN photodiode (WG-PD) become one of the solutions. The structure of WG-PD, which has an edge illuminated structure, is easy to fabricate because the structure is similar to conventional laser diodes. However, it has scarcely been reported the device has high reliability. Because most of WG-PD are passivated with polymide or SiN, which can't passivate sufficiently. Previously reported degradation mechanisms of WG-PD come from the accumulation of hole trapped at the generation-recombination center near the mesa surface [1] or the hot hole injection into the passivation film [2]-[4]. In order to raise reliability, we developed the WG-PD buried with semi-insulating indium phosphide (SI-InP) using metal organic chemical vapor deposition (MOCVD) [5]. But the diffusion of p type dopant has increased because of the temperature rising during the epitaxial growth. The diffusion needs higher operation voltage to realize wide bandwidth, which requires trans impedance amplifier with low operation voltage or additional bias cuircuit. Decreasing of the carrier density of p-InGaAsP, which is a separate confinement heterostructure layer between p-clad layer and absorption layer, can suppress diffusion of p-type dopant. However, it increases the resistance of PD has increased. In this report to suppress the diffusion of p-type dopant, we have inserted the spacer layer between i-InGaAs absorption layer and p-InGaAsP SCH layer. By adapting this structure, we can realize WG-PD buried with SI-InP, which has low bias operation, wide bandwidth and high reliability.

2. The structure of wave-guide photodiode

Figure 1 shows our WG-PD buried with SI-InP. A mesa wave-guide region is epitaxially grown on semi-insulating InP substrate using MOCVD. SI-InP substrate is employed to reduce parastic capacitance. A mesa wave-guide region is formed using wet-chemical etching, then, buried with SI-InP by using selective MOCVD growth technique. SI-InP passivates the mesa surface and planelizes the surface of the device. N-contact electrode is formed on n-InGaAs contact layer, which has been exposed by etching SI-InP off from the surface. Both of n- and p-electrodes are formed on the same side of chip. This structure is suitable for flip-chip bonding mounting in order to reduce the reactance of the interconnection. Finally, an antireflective film is deposited on the flont cleaved facet, which is SI-InP window region.

3. Frequency response

In general, if p-InGaAsP SCH layer is highly doped to reduce the resistance, then p-type dopant diffuses into i-InGaAs absorption layer. Higher carrier density of p-InGaAsP SCH layer to reduce resistance results in larger diffusion of p-type dopant into the i-InGaAs absorption layer. In this case, frequency response of WG-PD strongly depends on the operation voltage and WG-PD needs higher operation voltage. In this work, i-InGaAsP spacer layer is inserted between i-InGaAs absorption layer and p-InGaAsP SCH layer. This spacer layer reduces diffusion of