Undoped InP Sandwiched InGaAs p-i-n Photodetector with Partially p-Doped Photoabsorption Layer Grown on Linearly Graded Metamorphic $In_xGa_{1-x}P$ Buffered GaAs Substrate

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ABSTRACT

A novel top-illuminated In0.53Ga0.47As p-i-n photodiodes, with the partially p-doped photoabsorption layer, grown on GaAs substrate by using a linearly graded metamorphic InxGa1-xP (x graded from 0.49 to 1) buffer layer is reported. The dark current, optical responsivities, noise equivalent power, and operational bandwidth of the MM-PINPD with aperture diameter of 60 μm are 13 pA, 0.6 A/W, $3.4 \cdot 10^{-15}$ W/Hz$^{1/2}$, and 8 GHz, respectively, at 1550 nm. Under the illumination of 1.2-ps pulse-train, the measured impulse response is 41 ps and the frequency bandwidth is up to 8 GHz with heterodyne beating measurement. The low cost InGaAs photodiode with high current bandwidth product (350 mA•GHz, at 10 GHz) and bandwidth-efficient product (4.8 GHz•A/W) have been achieved.

Keywords: Metamorphic, $In_{0.53}Ga_{0.47}As$, InGaP, GaAs, p-i-n Photodiode, receiver, high-power photodiode

1. INTRODUCTION

Recently, different metamorphic (MM) epitaxial layers such as InGaAs [1], InAlAs [2, 3], InAs [4], InGaAlAs [5], etc. have emerged as the buffered layers for growing InGaAs-based optoelectronic devices on GaAs substrates with lowered cost. Compositionally graded metamorphic buffer layers are extensively utilized to accommodate large lattice mismatch between a semiconductor substrate and epitaxial layers, which overcomes the limitation of band-gap engineering imposed by the substrate lattice parameters. Technically, the metamorphic epitaxy facilitates some advantages from greater strength, no need of InP substrate, ready availability of large diameter substrates, easier material handling, and the compatibility with the existing manufacturing infrastructure. In general, photodiode made of narrow-band gap materials are operated under zero bias because of their high leakage current and low breakdown voltage. Infrared diodes are selected according to the resistance and area (RoA) product. However, the RoA product is degraded by increase in current leakage. Thus, there is interesting in investigating low-leakage photodetectors with high modulation frequency. However, another important challenge of photodetectors (PDs) is high optical saturation power. In digital fiber-optics systems, the PDs with high sensitivities are usually placed after an erbium-doped-fiber-amplifier or semiconductor optical amplifier. The new approach becomes attractive when high-saturation-current photodiodes are available, so that the output from the photodiode can directly drive a decision circuit. In this paper, we report for the fabrication of top-illuminated metamorphic p-i-n photodiodes (MM-PINPD) with partially p-doped photoabsorption layer [6, 7] on GaAs substrates using linearly graded InxGa1-xP buffer layer. We incorporated the partially p-doped photoabsorption layer and metamorphic structure to get a good balance of its electronic bandwidth, the capability of radio-frequency (RF) power generation, and cost-effective consideration. The MM-PINPD has the graded partially p-doped photoabsorption layer to accelerate the drift velocity of photogenertaed electron. Since the bandwidth of our previous structure [8] was not transit-time limited, in this letter, we modified the structure with partially p-doped photoabsorption layer. Compared to our previous work, the new structure demonstrated nearly the higher saturation current and higher bandwidth of 8 GHz without sacrificing the responsivity. The demonstrated

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metamorphic epitaxy is particularly suitable for mass-production of such devices on GaAs substrates. Ultralow leakage current, high operated bandwidth, and high saturation current product performances have been achieved simultaneously. By using such a metamorphic buffer and partially p-dope, an InGaAs PINPD with a very low dark current density, high operated bandwidth, and high saturation current product was reported. These results interpret the capability of such a device for application in 10G-bit/s SONET/SDH networks or 5-GHz radio-over-fiber systems.

2. EXPERIMENTAL SETUP

rior to the growth InGaAs MM-PINPD structure, a 1.5μm-thick linearly graded metamorphic InxGa1-xP buffered layer with x gradually changing from 0.49 to 1 was deposited on a 3-in (100)-oriented semi-insulating (SI) GaAs by using gas source molecular beam epitaxy (GSMBE) at substrate temperature of 500°C. An InGaAs MM-PINPD was subsequently grown at 600°C, which consists of 1μm-thick n+-InP, 0.5μm-thick undoped InP, 2.5 μm-thick undoped $In_{0.53}Ga_{0.47}As$, and 1μm-thick graded doping p-InP (after Zn diffusion) layers as shown in Fig. 1. After epitaxy, the coplanar guard-ring typed ground-signal-ground contact electrodes with circular window diameter of 60 μm, two n-types ground contact pads and one central p-type contact pad are fabricated by evaporating 800nm-thick Ni/Au and Ti/Au metals, respectively. Fig 2 shows a band diagram of the MM-PINPD at reversed bias 5 V. This design facilitates the diagnostics of the InGaAs MM-PINPD by a lightwave probe station with a 65-GHz coplanar-waveguide typed millimeter-wave probe (Picoprobe 65A-GSG-70-P) as shown in the inset of Fig. 2.

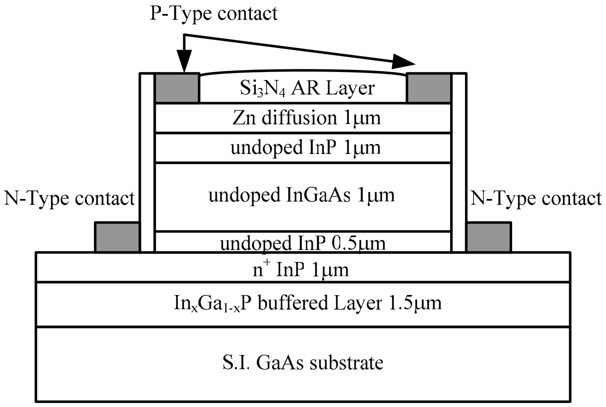

Fig. 1. The configuration of an InGaAs PINPD made on metamorphic InGaP buffered semi-insulating GaAs substrate

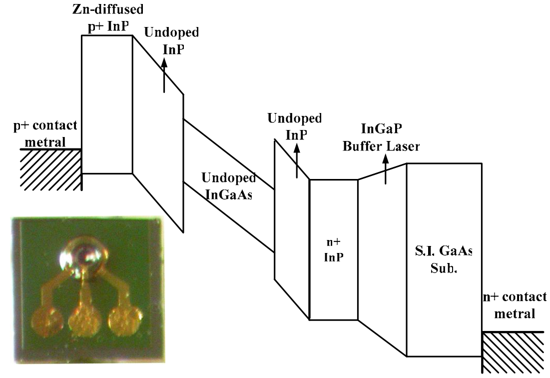

Fig. 2. The conceptual band diagram of the MM-PINPD at reversed bias 5 V; and the inset shows the top-view photograph of the MM-PINPD.

A bias-tee circuit was employed to combine negatively bias voltage and to separate the transient photocurrent response of the metamorphic InGaP buffered InGaAs MM-PINPD. The bandwidth and saturation current were measured with a heterodyne beating [8] setup as shown in Fig. 3. A tunable laser was employed as the light source which has a 1550-nm center wavelength for the dc measurement. The outputs of two tunable laser sources were mixed in a 3-dB coupler. The beating signal tuning by two tunable lasers was adopted. An optical attenuator and a high-power erbium doped fiber amplifier (EDFA) were connected to the output of coupler to adjust the input power. The beating frequency and frequency response of the MM-PINPD were measured by a 40GHz RF spectrum analyzer and a 50-GHz RF power meter (Agilent/HP E4417A and 8487A). The TE/TM polarization dependence of the measurement responsivity was around 0.5 dB. The influences of microwave probe, RF cable, RF bias-tee, and RF adapters on measured frequency response were removed by use of RF correction technique and a 50-GHz network analyzer [10]. All measurements were conducted at room temperature.

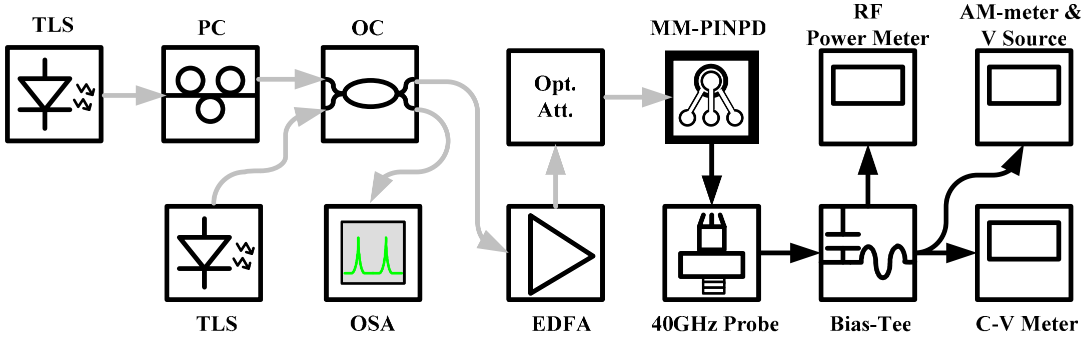

Fig. 3. The diagnostic setup of the heterodyne beating measurement for the coplanar guard-ring typed InGaAs PINPD. PC: polarization controller, Opt. Att.: optical attenuator, TLS: tunable laser source, OSA: optical spectrum analyzer.

3. RESULTS AND DISCUSSION

The structure of InGaAs MM-PINPD is similar as previous reports except the whole structure were grown on semi-insulating substrate [11]. The metamorphic buffer absorbs the strain of lattice mismatch and prevents the vertical propagation of dislocations, thereby maintaining the quality of the device active layers. The dark current of the MM-PINPD on GaAs substrate is an effective measurement of the quality of the metamorphic buffer layer. The dark currents of photodiodes were highly dependent upon the metamorphic buffer layer. The continuously graded buffer layer provides lower dark currents, with a buffer structure in which indium and gallium concentrations are ramped inversely. A thick InGaP buffer layer can generate a high density of defects that results in high dark currents because of the unfiltered lattice-mismatch strain and the difference in thermal expansion coefficients between InGaP and the GaAs substrate. Therefore, the magnitude of dark currents could reflect the quality of InGaP metamorphic layer. The I-V responses under 1550-nm CW light: (a) 0 dBm, (b) -20 dBm, (c) -40 dBm, (d) -60 dBm, (e) -80 dBm, (f) dark current of the negatively biased MM-PINPD with 60-μm diameter is plotted in Fig. 4. Even with the metamorphic layer, an extremely low dark current of 13 pA is obtained at a bias voltage of -5 V. Such a leakage current density is almost three orders of magnitude lower then the previously reported InGaAs MM-PINPD made on GaAs a different metamorphic buffered layer [12], which reveals the improvement in lattice grading property between InGaAs layer and GaAs substrate with the adding of metamorphic InGaP buffer. For fair comparison with Ref. 12, the dark current under -18 V bias, which in order to meet the same electric filed in the InGaAs layer, was measured as 15.5 pA. Due to its extremely low dark current density of 3.6×10^{-7} A/cm^2, the minimum detectable power is as low as 10 pW. Compositionally graded metamorphic buffer layers are extensively utilized to confine threading dislocations and defects in the metamorphic InGaP buffer without propagating vertically into the device layer. The InP layer can be very smooth since there is no compositional control problem in the InGaP/InP system. Furthermore, since the bandgap of InGaP is larger than that of InP, a fully transparent buffer layer can be achieved. The TEM analysis and the ultra-low dark current response of the p-i-n PD also reveals the device layers upon the metamorphic buffer which are nearly dislocation-free (with density of 1×10^6 cm-^{2}). InP-InGaAs-InP layer with sandwiched structure leads to broaden equivalent width of InGaAs, and this structure is suit to high- voltage and electrical-field operation. Carriers are trapped at the sandwiched structure which results in ultralow dark current due to the higher band gap of InP than that of InGaAs. In comparison, these results are comparable to those of a commercial PINPD (Emcore, InGaA/InP PINPD, model 8413-1155) with current density of 6.2×10^{-5} A/cm^2 at a bias of -3.5 V. Our proposed MM-PINPD exhibits better performance of current density than this commercial one. Such a low dark current not only reveals the better lattice-matching property between the InGaP buffer and the GaAs substrate, but also gives to a minimum detectable power of below 100 pW. These results again reflect that reducing the leakage current is a decisive way to improve the sensitivity of MM-PINPD owing to the significant suppression on noise equivalent power of the receiver module. The shot and thermal noises of the InGaAs MM-PINPD without a matching circuit are calculated as 6.9×10^{-11} A and 1.1×10^{-12} A, respectively.

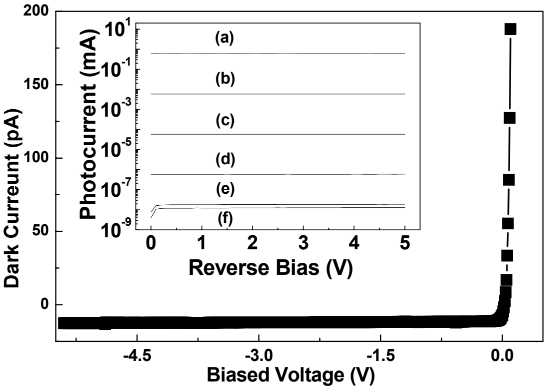

Fig. 4. Dark current versus biased voltage from 0.1 V to -5 V for MM-PINPD, showing a 13 pA leakage current at -5V. The inset figure shows the photocurrent of MM-PINPD under 1550-nm CW light: (a) 0 dBm, (b) -20 dBm, (c) -40 dBm, (d) -60 dBm, (e) -80 dBm, (f) dark current.

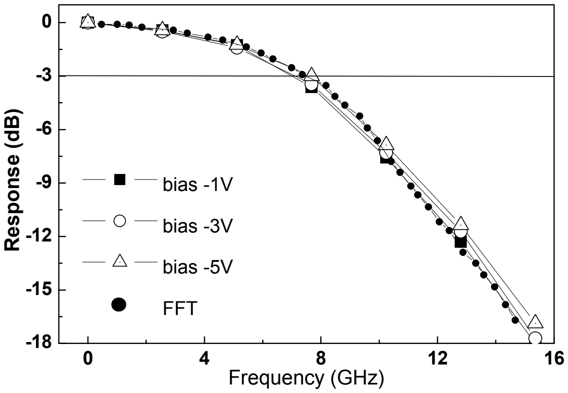

Fig. 5 Measured frequency responses under photocurrent of 1mA and bias voltage of -1 V, -3V, and -5V. The solid dot shows the frequency response from the fast Fourier transform.

For a reversely biased PINPD device, it is important to minimize the leakage and obtain high-response. The carrier transit time can be shortened by reducing the thickness of the absorption layer, reducing the device leakage current and obtaining a high-speed response. However, reducing the absorption layer thickness of the absorption usually lead to a lower quantum efficiency. The photocurrent of the InGaAs MM-PINPD measured at a reverse bias of 5 V is 0.6 mA, under an illuminating power of 0 dBm, corresponding to an optical responsivity of 0.6 A/W which indicates that the p-doped photoabsorption layer of our structure does not sacrifice the performance of quantum efficiency. In order to further study the speed and power performances of our MM-PINPD, the frequency response was measured under photocurrent of 1mA and different voltage of reversed bias (-1, -3, -5 V) by using heterodyne beating, as shown in Fig. 5. One can be clearly see that under bias from -1 to -5 V, the electrical bandwidth was around 8 GHz. The frequency response was also verified by using impulse response. The mode-locked fiber laser [13] with a full width at half maximum (FWHM) of 1.2 ps was served as an input source. The impulse response of the MM-PINPD reveals a FWHM of 40 ps, which indicates the bandwidth of 8 GHz from the fast Fourier transform. The bandwidth-efficient product of 4.8 GHz•A/W of proposed MM-PINPD was measured.

The traces in Fig. 6 show the RF power versus photocurrent of the MM-PINPD under different bias voltage (-1, -3, -5 V) with operating frequency of 10 GHz and the dc saturation characteristic was shown in the inset of Fig. 6. The ideal relation between the RF power of 100% modulated large signal and the average current on a 50-ohm load is also plotted as a straight line for reference. The demonstrated maximum values of the generated RF power and the averaged photocurrent of the device were limited by the device failure under high current operation. The current-bandwidth product of our MMPIN-PD was measured as 350 mA•GHz. The maximum RF power of 1 dBm and photocurrent of 35 mA can be respectively obtained, and the value were higher than those reported in previous work on top- illuminated p-i-n photodetectors with such low leakage current. These measurement results, indicate that the technique of partially p-doped photoabsorption layer enhance the speed and output power performance of photocurrent significantly without sacrificing the device performance. The improvement in high-power performance of photodiode is due to the fact that the p-doped region can shorten the depletion width of the photoabsorption layer, reduce the space charge field of photogenergated carriers, and increase the output saturation current effectively. The photogeneration of holes in the intrinsic layer of the MM-PINPD can result in larger space charge effects than those in the structure. However, this effect is not as severe if the drift layer is thin. For these reasons, the MM-PINPD can be operated under low bias voltage to reduce the total power consumption, while still suppressing saturation. Furthermore, as compared to less thickness of intrinsic InGaAs photoabsorption layer, this technique on our MM-PINPD does not increase the device absorption length or sacrifice the repsonsivity.

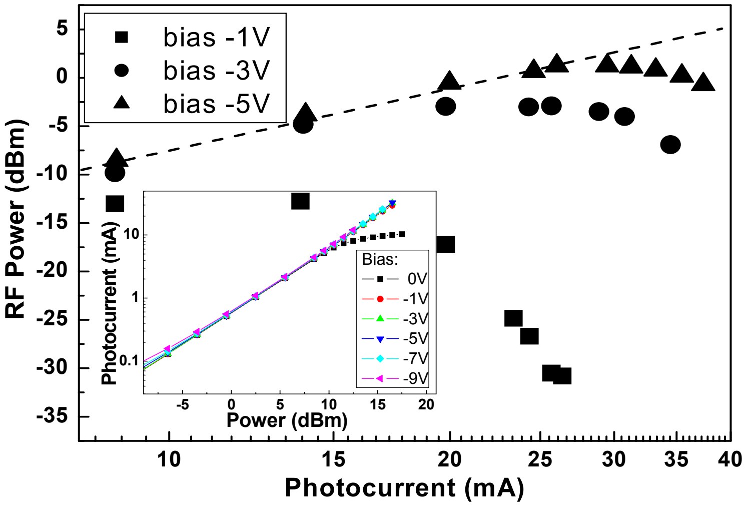

Fig. 6. RF power versus photocurrent under the reversed bias of 1, 3, 5 V at a 10-GHz operating frequency and the inset shows the dc saturation characteristic.

4. CONCLUSION

In conclusion, low-leakage undoped InP sandwiched In0.53Ga0.47As p-i-n photodiode with the partially p-doped photoabsorption layer on GaAs with linearly graded metamorphic InxGa1-xP buffer layer has been demonstrated. The dc and radio frequency performance of the photodiodes are characterized. At a bias of -5 V, the MM-PINPD with aperture diameter of 60 m exhibits a dark current of only 13 pA. The optical responsivities of 0.77 A/W and 0.6 A/W, and the NEP of 2.7 10-15 W/Hz1/2 and 3.4´10-15 W/Hz1/2, have been determined at 1310 nm and 1550 nm, respectively. The broad 3-dB bandwidth (over 8 GHz) and high saturation photocurrent (over 35mA) with corresponding 350 mA•GHz current bandwidth product at 10 GHz operating frequency was reported. By utilizing the technique of partially p-doped photoabsorption layer, the demonstrated MM-PINPD has improvement in high-power performance without sacrificing its speed and responsivity performance.

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REFERENCES

1. H. Ito, S. Kodama, Y. Muramoto, T. Furuta, T. Nagatsuma, T. Ishibashi, “High-Speed and High-Output InP-InGaAs Unitraveling-Carrier Photodiodes,” IEEE J. of Sel. Topics in Quantum Electronics, vol. 10, pp.709-727, 2004.
2. S. Demiguel, N. Li, X. Li, X. Zheng, J. Kim, J. C. Campbell, H. Lu, and A. Anselm, “Very High-Responsivity Evanescently Coupled Photodiodes Integrating a Short Planar Multimode Waveguide for High-Speed Applications,” IEEE Photon. Technol. Lett., vol. 15, pp.1761-1763, 2003.
3. X. Li, N. Li, S. Demiguel, X. Zheng, J. C. Campbell, H. H. Tan, and C. Jagadish, “A Partially Depleted Absorber Photodiode With Graded Doping Injection Regions,” IEEE Photon. Technol. Lett., vol. 16, pp.2326-2328, 2004.
4. V. Hurm, W. Benz, W. Bronner, M. Dammann, T. Jakobus, G. Kaufel, K. Kohler, Z. Lao, M. Ludwig, B. Raynor, J. Rosenzweig, M. Schlechtweg, “10 Gbit/s long wavelength pin-HEMT photoreceiver grown on GaAs,” Electron. Lett., vol. 33, pp. 1653-1654, 1994.
5. M. Zaknoune, M. Ardouin, Y. Cordier, S. Bollaert, B. Bonte, and D. Théron, “60-GHz high power performance In0.35Al0.65As-In0.35Ga0.65As metamorphic HEMTs on GaAs,” Electron. Lett., vol. 36, pp. 741-742, 2003.
6. X. Li, N. Li, S. Demiguel, X. Zheng, J. C. Campbell, H. H. Tan, and C. Jagadish, “A partially depleted absorber photodiode with graded doping injection regions,” IEEE Photon. Technol. Lett., vol. 16, pp. 2326–2328, 2004.
7. Y.-S. Wu, J.-W. Shi, J.-Y. Wu, F.-H. Huang, Y.-J. Chan, Y.-L. Huang, and R. Xuan, “High-Performance

Evanescently Edge Coupled Photodiodes With Partially p-Doped Photoabsorption Layer at 1.55-μm Wavelength," IEEE Photon. Technol. Lett., vol. 17, pp. 878 – 880, 2005.

8. C.-K. Lin, H.-C. Kuo, M. Feng, G..-R. Lin, "Ultralow Leakage In0.53Ga0.47As p-i-n Photodetector Grown on Linearly Graded Metamorphic InxGa1-xP Buffered GaAs Substrate," IEEE J. Quantum Electron., vol. 41, pp. 749-752, 2005.
9. F. Xia, J. K. Thomson, M. R. Gokhale, P. V. Studenkov, J. Wei, W. Lin, and S. R. Forrest, "A asymmetric twin-waveguide high-bandwidth photodiode using a lateral taper coupler," IEEE Photon. Technol. Lett., vol. 13, pp. 845–847, 2001.
10. Z.-Y. Chen, Y.-L.Wang, Y. Liu, and N.-H. Zhu, "Two-port calibration of test fixtures with OSL method," in Proc. 2002 3rd Int. Conf. Microwave and Millimeter Wave Technology, pp. 138–141.
11. Z. Griffith, Y.-M. Kim, M. Dahlström, A. C. Gossard, and M. J. W. Rodwell, "InGaAs–InP Metamorphic DHBTs Grown on GaAs With Lattice-Matched Device Performance and ft, fmax > 268 GHz," IEEE Electron. Lett., vol. 25, pp. 675-677, 2004.
12. J.-H. Jang, G. Cueva, W. E. Hoke, P. J. Lemonias, P. Fay, and I. Adesida, Fellow, "Metamorphic Graded Bandgap InGaAs–InGaAlAs–InAlAs Double Heterojunction P-i-I-N Photodiodes," J. of Lightwave Technol. vol. 20, pp. 507-514, 2002.
13. G.-R. Lin, I.-H. Chiu, and M.-C. Wu, "1.2-ps mode-locked semiconductor optical amplifier fiber laser pulses generated by 60-ps backward dark-optical comb injection and soliton compression," Optics Express, vol. 13, pp. 1008-1014, 2005.