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Ultralow Leakage $In_{0.53}Ga_{0.47}As$ p-i-n Photodetector Grown on Linearly Graded Metamorphic $In_xGa_{1-x}P$ Buffered GaAs Substrate

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***Abstract*—A novel top-illuminated $In_{0.53}Ga_{0.47}As$ p-i-n photodiodes (MM-PINPD) grown on GaAs substrate by using linearly graded metamorphic $In_xGa_{1-x}P$ (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, 3.4×10^{-15} W/Hz$^{1/2}$, and 7.5 GHz, respectively, at 1550 nm. The performances of the MM-PINPD on GaAs are demonstrated to be comparable to those of a similar device made on InGaAs–InP substrate.**

***Index Terms*—GaAs, InGaP, $In_{0.53}Ga_{0.47}As$, metamorphic, p-i-n photodetector.**

I. INTRODUCTION

LONG-WAVELENGTH p-i-n photodiodes (PINPD) with $In_{0.53}Ga_{0.47}As$ absorption layer for fiber-optic communication networks have been fabricated on the lattice-matched InP substrate over several decades. The InGaAs PINPD made on lattice-matched InP substrate provides low noise, high gain, and high frequency characteristics as compared to that made on GaAs. However, InP suffers from several drawbacks including higher fragility, less mature processing technologies, and smaller available wafer sizes compared to GaAs. 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, such as laser diode [1], [6], photodiodes [5], high electron mobility transistors [2], [3], heterojunction bipolar transistor (HBT) [4], optoelectronic integrated circuit, [7] etc. 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 bandgap engineering imposed by the substrate lattice parameters. Threading dislocations and defects are mainly confined within the metamorphic buffer without propagating vertically into the device layer structures. Technically, the metamorphic epitaxy facilities 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. These lead to a cost effective solution without sacrificing the device performance. The aluminum-contained material systems have earlier been proposed for the growth of graded buffer layers on GaAs substrate. However, the aluminum containing layers in the optoelectronic devices are known to exhibit problems such as deep traps and rapid oxidation. Recently, a few studies have been carried out to replace the Al-containing materials by using InGaP as the buffer layer [8] with its lattice constant gradually varying from that of GaAs to that of InP. The use of InGaP graded layer thus benefits from the possibility of growing InP-Based heterostructures on GaAs, GaP, and Si substrate. Moreover, the transition between the graded buffer ($In_xGa_{1-x}P, 0 < x < 1$) and the InP layer can be very smooth since there is no compositional control problem in the InGaP– InP system. This is unlike the case of InAlAs or InGaAs buffer layers, where the switching of As to P at the interface usually generates a thin ternary or quaternary interfacial layer. Furthermore, since the bandgap of InGaP is larger than that of InP, a fully transparent buffer layer can be achieved, which is advantageous for long-wavelength optoelectronic devices. Nonetheless, only a few optoelectronic applications in InGaP– GaAs system were reported except for the metamorphic InGaP-buffered high-electrom mobility transistor (HEMT) and HBT [9], [10]. In this paper, we report for the first time the fabrication of top-illuminated metamorphic p-i-n photodiodes (MM-PINPD) on GaAs substrates using linearly graded $In_xGa_{1-x}P$ buffer layer. The demonstrated metamorphic epitaxy is particularly suitable for mass-production of such devices on GaAs substrates. Dark currents, responsivities, and operational bandwidths of MM-PINPD with an aperture diameter of 60 μm are reported.

II. EXPERIMENTAL

The MM-PIN heterostructure was grown on a 3-in (100)-oriented n-type GaAs substrate using gas source molecular beam epitaxy, as shown in Fig. 1(a). A buffer layer consisting of 1.5-μm-thick undoped $In_xGa_{1-x}P$ (xx linearly and gradually changed from 0.49 to 1) was grown at 470 °C. Afterwards, the PINPD with a layer structure of n^+-InP (1 μm)/undoped InP (0.5 μm)/undoped $In_{0.53}Ga_{0.47}As$ (2.5 μm)/undoped InP (1 μm) was grown upon the MM layer at 550 °C. A p-type InP ohmic contact was formed by evaporating a 0.8-μm-thick

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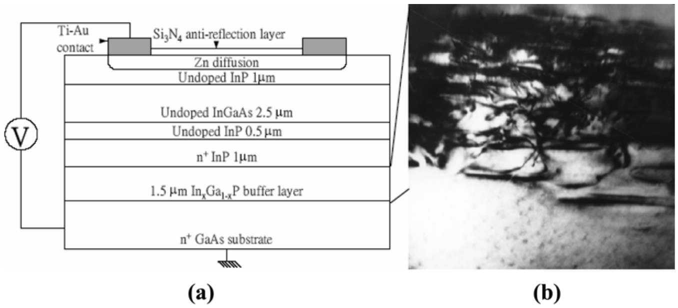

Fig. 1. (a) Layer structure of a MM-PINPD on GaAs. (b) Cross-sectional TEM photograph of a linearly-graded $In_xGa_{1-x}P$ metamorphic buffer layer.

Ti–Au metal on a Zn-diffused InP window layer. The bond-pad of 80 μm is off the side to the active area with diameter of 60 μm. A Si_3N_4 dielectric layer was deposited on the active region (with diameter of 60 μm) of the MM-PINPD device surface for passivation and antireflection. The active area of the MM-PINPD was laterally isolated from the rest of the wafer by a reactive-ion-etched trench, and was vertically isolated by a high bandgap cladding layer. The MM-PINPD chip was mounted on a SMA connector with its n-type GaAs substrate connecting to the pin of SMA, as shown in Fig. 2. A metal probe was employed to negatively bias the p-type contact on MM-PINPD. The capacitance of the MM-PINPD with SMA mount was measured by a capacitance-voltage meter (Hewlett Packard, 4280A) at modulation frequency of 1 MHz. The current–voltage (I–V) response was measured using a programmable electrometer (Keithley, model 6517) with resolution as low as 100 fA. The responsivity linearity and responsivity versus wavelength ranged from 1310 to 1550 nm were determined using tunable lasers (Hewlett Packard, 8168F) and distributed feedback laser diodes (DFBLDs) in connection with an attenuator (JDS-FITEL, HA9). For high-speed performance, the DFBLDs were gain-switched to generate the pulse-train with full-width at half-maximum (FWHM) of 42 ps at a repeating rate of 1 GHz. The temporal response of the MM-PINPD was monitored on a digital sampling oscilloscope (DSO, Hewlett Packard, 86 100A+86 109B). All measurements were conducted at room temperature.

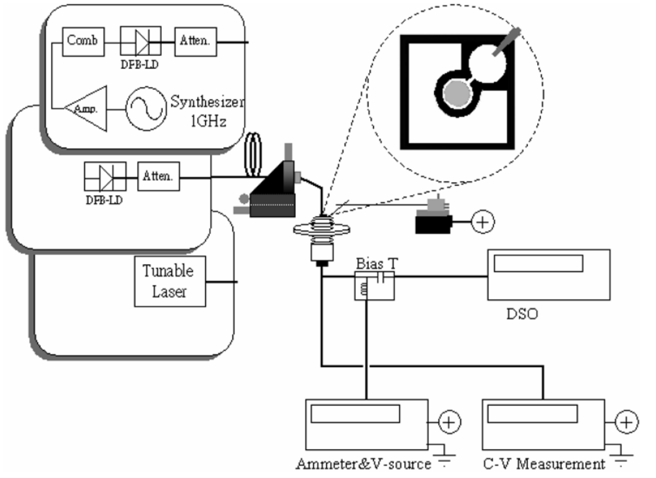

Fig. 2. Diagnostic setup for the SMA mounted InGaAs MM-PINPD on GaAs. Amp.: electrical amplifier; atten.: optical attenuator; DFB-LD: distributed feedback laser diode; DSO: digital sampling oscilloscope.

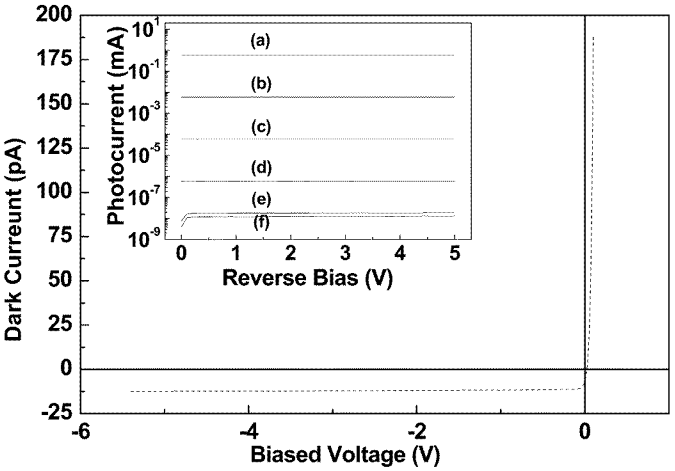

Fig. 3. Dark current versus biased voltage from 0.1 V to −5 V for MM-PINPD, showing a 13-pA leakage current at −5 V. The inset figure shows the photocurrent of MM-PINPD under 1550-nm continuous wave (CW) light: (a) 0 dBm; (b) −20 dBm; (c) −40 dBm; (d) −60 dBm; (e) −80 dBm; (f) dark current.

III. RESULTS AND DISCUSSIONS

The surface morphology of the epilayers was *in situ* controlled by monitoring the reflection high energy electron diffraction pattern. The composition, structural quality and the degree of strain relaxation were subsequently evaluated by high-resolution x-ray diffraction and the cross section transmission electron microscope (TEM) image. In Fig. 1(b), the cross section at view of the metamorphic buffer layer taken by TEM shows a dense dislocation network that was formed during the grading layer to expand the lattice constant. In general, 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 density of dislocations, predominantly contained in the metamorphic buffer layer, of 1×10^6 cm^{-2} was estimated from the plain-view image of TEM. The device layers upon the metamorphic buffer are nearly dislocation-free. The I–V response of the negatively biased MM-PINPD with 60-μm diameter is plotted in Fig. 3. Even with the metamorphic layer, an extremely low dark current of 13 pA is obtained at a bias voltage of −5 V, which is comparable to that of a similar PINPD made on InP substrate. Previously, Jang *et al.* have demonstrated a MM-PINPD with a p$^+$-InGaAs–InGaAs/n$^+$–InAlAs p-i-n structure on a linearly graded InAlGaAs buffer layer [11], in which the $In_{1-x-y}Ga_xAl_yAs$ layer serves as a lattice-constant transformer between the GaAs substrate and the $In_{0.53}Ga_{0.47}As$ layers. By using such a metamorphic buffer, an InGaAs PINPD with a very low dark current density of 3.4×10^{-4} A/cm^2 at bias of 5 V and an optical responsivity of 0.55 A/W at 1.55 μm was reported. In comparison, the corresponding leakage current density of 3.6×10^{-7} A/cm^2 for the InGaP-buffered MM-PINPD on GaAs is almost three

TABLE I
PARAMETRIC COMPARISON ON THE DIAMETER, RESPONSITIVITY (R), NEP, RISE TIME (t_r), DARK CURRENT (I_d), AND CAPACITANCE (C) BETWEEN THE MM-PINPD AND THE COMMERCIAL PRODUCT (EDMUND'S INGAAS PD)

	Diameter (μm)	R (A/W) (1.31/1.55 μm)	NEP (W/Hz$^{1/2}$)	t_r (max) (ps)	I_d (pA)	C (pF)
Edmund InGaAs PD	70	0.9/0.95	3.4×10^{-15}	200	30	0.65
MM-PINPD	60	0.77/0.59	3.4×10^{-15}	52	13	0.53

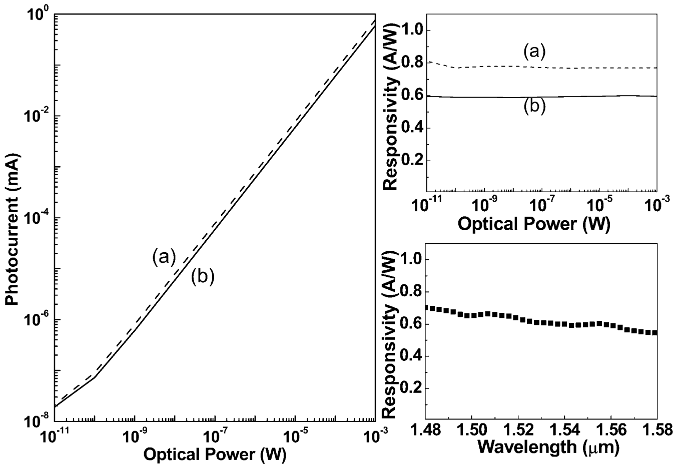

Fig. 4. Left: the inset figure shows the responsivities of the MM-PINPD at different wavelengths and powers. The optical responsivities of the MM-PINPD as a function of optical power (upper right) and wavelength (lower right) at (a) 1310 nm and (b) 1550 nm.

orders of magnitude smaller. Such a low dark current reveals the better lattice grading property between the InGaP buffer and the GaAs substrate in this study.

The power- and bias-dependent photocurrent of MM-PINPD illuminated at 1550-nm wavelength is shown plotted in the inset of Fig. 3. At a reverse bias of 5 V, The photocurrents measured at the illuminating power of 0 dBm is 0.6 mA, corresponding to an optical responsivity of 0.6 A/W. The photocurrent of MM-PINPD decreases from 0.6 mA to 0.6 nA as the illuminating power attenuates from 0 to -60 dBm, while a linear relationship between the illuminating power and the corresponding photocurrent is found, as shown in Fig. 4. The responsivity of the MM-PINPD is extremely linear, which is even detectable at the illuminating power of below 100 pW due to its extremely low dark current. Moreover, the photocurrents and optical responsivities at 1310 and 1550 nm were also compared in Fig. 4. The optical responsivity R of the MM-PINPD is calculated using $R = (I_{\rm ph} - I_d)/P_{\rm laser}$, where $I_{\rm ph}$ and I_d denote the photocurrent and dark current of the MM-PIDPD, and $P_{\rm laser}$ is the laser power at the illuminating end. Under an illuminating power of 0 dBm, the optical responsivities at 1310 and 1550 nm are 0.77 and 0.6 A/W, respectively. The optical responsivities are also higher than those of a similar double-heterojunction PINPD made on InAlGaAs GaAs substrate [11]. The quantum efficiency ($\eta = N_{\rm e}/N_{\rm ph} = I_{\rm photo}{\rm h}\nu/\delta P_{\rm in}$) of the MM-PINPD is calculated as 83% at 1310 nm under a measured insertion loss of 0.58 dB, where the N_e and $N_{\rm ph}$ represent number of electrons and photons, respectively, $I_{\rm photo}$ denotes the photocurrent of the MM-PIDPD, $P_{\rm in}$ is the corresponding laser power, h is Plank constant, ν is the center frequency of injected light, and δ overall optical losses of the guiding system for laser. As a reference, the responsivity of state-of-the-art InGaAs photodiode is up to 0.9 A/W. The responsivity discrepancy is mainly due to the thinner InGaAs thickness. The tuning of illuminating wavelength from 1480 to 1580 nm reveals a decreasing trend in responsivity (from 0.77 to 0.6 A/W), which is almost identical to the conventional $\rm In_{0.53}Ga_{0.47}As$ PINPD fabricated on InP substrate [12].

The capacitance (C) and the matching resistance (r) of the MM-PINPD with SMA mount measured at bias of -5 V are 0.525 pF and 50 Ω, which correspond to a theoretically calculated 3-dB bandwidth of 6×10^9 Hz. The shot and thermal noises of the MM-PINPD without the matching circuit are calculated as 6.9×10^{-11} A and 1.1×10^{-12} A, respectively. The shot-noise dominated noise equivalent power (defined as ${\rm NEP} = I_{\rm n}/R$, the ratio of detected noise current to the responsivity) of the MM-PINPD at 1550 and 1310 nm are 3.4×10^{-15} W/Hz$^{1/2}$ and 2.7×10^{-15} W/Hz$^{1/2}$, respectively. These correspond to the detectivity (defined as ${\rm D} = 1/{\rm NEP}$) values at 1550 and 1310 nm of 2.9×10^{14} Hz$^{1/2}$/W and 3.7×10^{14} Hz$^{1/2}$/W, respectively. In comparison, these results are comparable to those of a commercial PINPD (Edmund, InGaAs PINPD, model R55-753), as listed in Table I. Finally, by using a gain-switched DFBLD with a pulsewidth of 42 ps and an average power of 0.1 mW at a repeating rate of 1 GHz, the switching responses of the MM-PINPD corresponding to 1310- and 1550-nm pulses, respectively, are also shown in the inset of Fig. 5. There are multireflection signals observed as the gradually decaying side peaks in the temporal response, which is mainly attributed to the absence of the transimpedance amplifier (TIA) on SMA mount. Nevertheless, it is notable that MM-PINPD has excellence performance on rise time. The rising time of the MM-PINPD illuminated at 1310 and 1550 nm are 35.56 and 51.85 ps, respectively. The switching time is less than 250 ps. A Fourier transform of the pulsed response depicts that the operational bandwidth of the MM-PINPD can be up to 7.5 GHz even without any impedance matching circuitry, as shown in Fig. 5. Temporal and eye diagram analyzes of the received pseudo-random binary sequence data corroborates that the MM-PINPD is promising for receiving the SONET/SDH protocol at a bit rate up to 2.5 Gb/s or higher.

IV. CONCLUSION

In conclusion, low-leakage $\rm In_{0.53}Ga_{0.47}As$ p-i-n photodetector fabricated on GaAs substrate with linearly graded metamorphic $\rm In_xGa_{1-x}P$ buffer layer has been demonstrated.

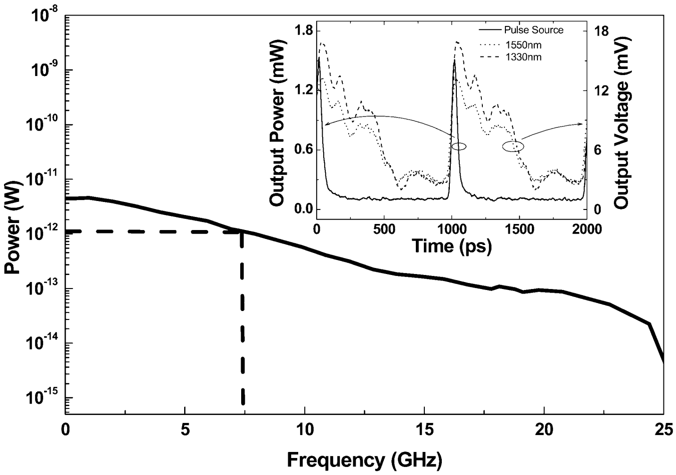

Fig. 5. Fourier transformed frequency response of the pulsed response of the MM-PINPD at 1550 nm. The inset shows the temporal traces of the MM-PINPD at 1310 and 1550 nm under the illumination of a gain-switched DFBLD at repetition frequency of 1 GHz.

The dc and radio frequency performance of the photodiodes are characterized. At a bias of -5 V, the MM-PINPD 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/Hz$^{1/2}$ and 3.4×10^{-15} W/Hz$^{1/2}$, have been determined at 1310 and 1550 nm, respectively. All the parameters are comparable to those of similar devices made on InP substrate or other InGaAs products epitaxially grown on an InGaAlAs buffered GaAs substrate. The operational bandwidth can be up to 7.5 GHz without reducing the diameter of aperture and managing the reflected signal by impedance matching.

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