10-Gb/s Operation of an $In_{0.53}Ga_{0.47}As$ p-i-n Photodiode on Metamorphic InGaP Buffered Semi-Insulating GaAs Substrate

Yu-Sheng Liao, Gong-Ru Lin, *Senior Member, IEEE*, Hao-Chung Kuo, *Member, IEEE*, Kai-Ming Feng, *Member, IEEE*, and Milton Feng, *Fellow, IEEE*

***Abstract*—The SONET OC-192 receiving performance of $In_{0.53}Ga_{0.47}As$ p-i-n photodiode grown on linearly graded metamorphic $In_xGa_{1-x}P$ buffered GaAs substrate is reported. With a low-cost TO-46 package, such a device exhibits a frequency bandwidth up to 8 GHz, a bit-error rate (BER) of 10^{-9} at 10 Gb/s, a sensitivity of -17.8 dBm, and a noise equivalent power of 3.4×10^{-15} W/Hz$^{1/2}$ owing to its ultralow dark current of 3.6×10^{-7} A/cm^2. Eye diagram analysis at 10 Gb/s without transimpedance amplification reveals a statistically distributed Q-factor of 8.21, corresponding to a minimum BER of 1.1×10^{-16} at receiving power of -6 dBm.**

***Index Terms*—Bit-error rate (BER), GaAs, $In_{0.53}Ga_{0.47}As$, InGaP, metamorphic, OC-192, p-i-n photodiode (PINPD), receiver.**

I. Introduction

INDIUM gallium arsenide (InGaAs) p-i-n photodiode (PINPD) is the most commonly used optical receiver in long-wavelength (from 1.1 to 1.65 μm) fiber-optic communication networks, which is usually made on lattice-matched InP substrate and offers advantages of low dark-current, high optoelectronic conversion efficiency, and moderately operational bandwidth. For cost-effective consideration, much effort has recently been made on growing the InGaAs materials upon GaAs wafers with lattice-matched buffered layers including InGaAs [1], InAlAs [2], InAs [3], InGaAlAs [4], and InGaP [5], etc. The monolithic integration and mass-production of InGaAs-based electronic and optoelectronic devices on GaAs substrate become available under the successful development of these metamorphic epitaxial techniques, which particularly meet the demand of rapidly increasing capacity on high-speed front-end transmitters and receivers employed in 10-Gb/s Ethernet protocol data or metropolitan communication systems [6].

Manuscript received October 11, 2005; revised March 20, 2006. This work was supported in part by the National Science Council under Grant NSC94-2215-E-009-040.

Y.-S. Liao and H.-C. Kuo are with Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.

G.-R. Lin is with the Graduate Institute of Electro-Optical Engineering and Department of Electrical Engineering National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: grlin@ntu.edu.tw).

K.-M. Feng is with Institute of Communications Engineering and Department of Electrical Engineering, National Tsing Hua University, Hsinchu, Taiwan 300, R.O.C.

M. Feng is with Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, IL 61801 USA.

Digital Object Identifier 10.1109/LPT.2006.877623

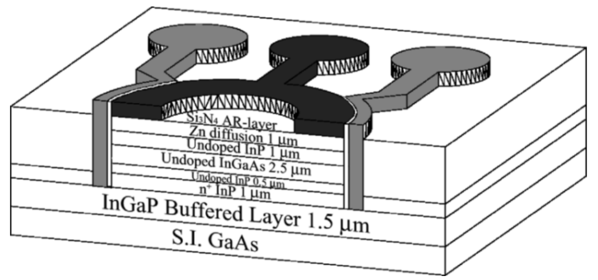

Fig. 1. Configuration of an InGaAs PINPD made on metamorphic InGaP buffered semi-insulating GaAs substrate.

That is, the low-cost and high-performance optical receivers are essential to the survival of such cost-sensitive, medium-short-reach, or short-reach fiber-optic communication systems. We have previously demonstrated a top-illuminated metamorphic InGaAs PINPD (MM-PINPD), fabricated upon a linearly graded $In_xGa_{1-x}P$ buffered GaAs substrate. In this work, the included impulse response, eye diagram, sensitivities, and bit-error rate (BER) of the InGaAs MM-PINPD with a coplanar pad made on metamorphic InGaP buffered semi-insulating GaAs substrate are determined. Furthermore, the OC-192 receiving performances of a Transistor Outline (TO)-46 can-packed fiber-optic receiver module comprising the MM-PINPD and transimpedance amplifier (TIA) are characterized.

II. Experiment

Prior to the growth InGaAs MM-PINPD structure, a 1.5-μm-thick linearly graded metamorphic $In_xGa_{1-x}P$ buffered layer, with x gradually increasing from 0.49 to 1, was deposited on a 3-in (100)-oriented semi-insulating GaAs by using gas source molecular beam epitaxy at substrate temperature of 500 °C. Subsequently, an InGaAs MM-PINPD was grown at 600 °C, consisting of 1-μm-thick n^+-InP, 0.5-μm-thick undoped InP, 2.5-μm-thick undoped $In_{0.53}Ga_{0.47}As$, and 1-μm-thick p-InP (after Zn diffusion) layers, as shown in Fig. 1.

The structure of InGaAs MM-PINPD is the same as reported before [6]. After epitaxy, the coplanar guard-ring-type ground-signal-ground contact electrodes with a diameter of 60 μm, two n-type ground contact pads, and one central p-type contact pad are fabricated by evaporating 800-nm-thick Ni–Au and Ti–Au metals, respectively. This design facilitates the diagnostics of the InGaAs MM-PINPD by a lightwave probe station with a 65-GHz coplanar-waveguide-type millimeter-wave probe (Picoprobe 65A-GSG-70-P). The responsivity was measured under the condition of using a lens fiber to focus the continuous-wave optical power onto the PD. The lens fibers

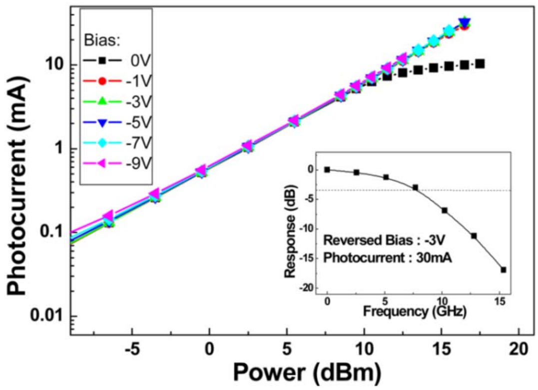

Fig. 2. Input optical power versus photocurrent under bias voltages from 0 to −9 V. The inset shows the measured OE frequency response under photocurrent of 30 mA and bias of −3 V. (Color version available online at http://ieeexplore.ieee.org.)

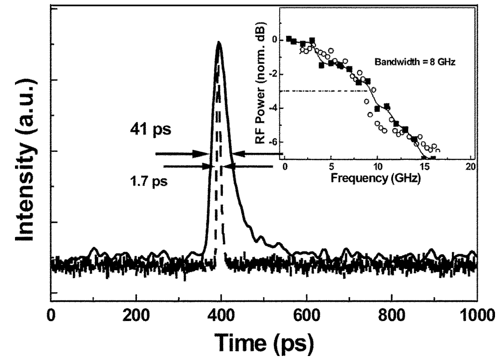

Fig. 3. Switching responses of the InGaAs PINPD at 1550 nm. The inset shows the calculated and measured frequency responses.

focus most optical power into the photodiode with active diameter of 60 μm and no coupling loss was estimated by using lens fibers. The impulse response was determined by illuminating the InGaAs MM-PINPD with a harmonically mode-locked and soliton compressed semiconductor optical amplifier fiber laser (SOAFL) of 1.2-ps pulsewidth at a repetition frequency of 1 GHz [7]. The temporal waveform of the InGaAs MM-PINPD was monitored on a digital sampling oscilloscope (Agilent/HP $86100A + 86116A, f_{3\ \mathrm{dB}} > 63$ GHz and $t_{\mathrm{FWHM}} = 7.5$ ps). At last, the InGaAs MM-PINPD was assembled with a TIA into a TO-46 can, and a ball lens was used to focus the light from a single-mode fiber onto the InGaAs MM-PINPD with an optical coupling loss of 4 dB by using TO-46 package. Parallel bond wires were employed to reduce parasitical inductance generated between the InGaAs MM-PINPD and preamplifier. The sensitivity and BER analyses were carried out under the illumination of a tunable laser, which was encoded with a pseudorandom binary sequence (PRBS) data stream by a BER analyzer (Agilent, 71612B) at a bit rate up to 12.5 Gb/s.

III. Results and Discussion

Fig. 2 shows power-dependent photocurrent of InGaAs MM-PINPD grown on a GaAs substrate at different biased voltages. The photocurrent response is extremely linear at an illuminating photocurrent range between 60 pA and 24 mA, which becomes saturated at beyond 30 mA. Note that the report on the MM-PINPD with such high saturating power is premier. The inset shows the measured frequency response under photocurrent of 30 mA and bias voltage of −3 V. The minimum detectable power is as low as 10 pW due to its extremely low dark current density of 3.6×10^{-7} A/cm^2. The shot and thermal noises of the InGaAs MM-PINPD without a matching circuit were calculated as 6.9×10^{-11} A and 1.1×10^{-12} A, respectively [5]. The dark current under −18-V bias for the fair comparison with [6] was measured as 15.5 pA. Such a leakage current density reveals the improvement in confinement of threading dislocations and defects between InGaAs layer and GaAs substrate with the adding of metamorphic InGaP buffer. 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. Although the optical responsivity of a state-of-the-art InGaAs MM-PINPD made on InP substrate is up to 0.9 A/W, the performance of our proposed device is already better than that of a similar double-heterojunction InGaAs MM-PINPD made on InAlGaAs buffered GaAs substrate to date [4]. The capacitance of the InGaAs MM-PINPD measured under impedance matching condition is 0.5 pF at 1 GHz, indicating a theoretically estimated 3-dB frequency bandwidth of 7 GHz or higher. The transient photocurrent trace of the InGaAs MM-PINPD under the illumination of SOAFL pulses at average power of 0.1 mW is shown in the Fig. 3. The rising time and falling time of the InGaAs MM-PINPD are 34.36 and 38.55 ps, respectively. The full-width at half-maximum (FWHM) switching response is 41 ps. The inset of Fig. 3 illustrated the frequency responses of the InGaAs MM-PINPD under photocurrent of 1 mA and bias voltage of −5 V, estimated from the fast Fourier transform of the temporal response and measured by using a commercial lightwave component analyzer (Agilent/HP 8703A, 0.13–20 GHz) at 1550 nm, providing the 3- and 6-dB frequency bandwidths of 8 GHz and >12 GHz, respectively. The bandwidth-responsivity product of 4.8 GHzA/W of proposed MM-PINPD was measured.

Later on, the eye-diagram analysis at 9.953 Gb/s is also performed to characterize the data receiving performance of the InGaAs MM-PINPD in a simulated SONET OC-192 fiber-optic network. This is done with an electronic time-division-multiplexing experiment using a 10-Gb/s optical PRBS data stream (with nonreturn-to-zero (NRZ) pattern length of $2^{23} - 1$ and optical input power of −6 dBm). Fig. 4(a) shows the received eye pattern measured at the MM-PINPD output without additional TIA. Besides, a well-opened eye pattern can be obtained with a relatively large dynamic range during a measuring time of 15 min. The rising time and falling time (defined as the duration between 20% and 80% of on-level amplitude) are 37 and 33 ps, respectively. The rms jitter of 4.86 ps was measured by determining the mean and standard deviation of a sampled eye-pattern histogram in the time domain. The monitored intensity noise on the eye pattern is close to the system limit (∼10 mV) of our digital sampling oscilloscope even without a TIA. Bergano *et al.* have previously demonstrated a BER evaluation method by measuring the signal-to-noise ratio at decision circuit of an optical transmission and receiving system [8], [9], which is given by $Q = (I_i - I_0/(\delta_1 + \delta_0)$ and BER $= (1/2)\mathrm{erfc}(Q/\sqrt{2})$, where $I_{1,0}$ and $\sigma_{1,0}$ are the mean value and standard deviation of the mark and space data rail, and $\mathrm{erfc}(x)$ is the complementary error function. The measured BER of the

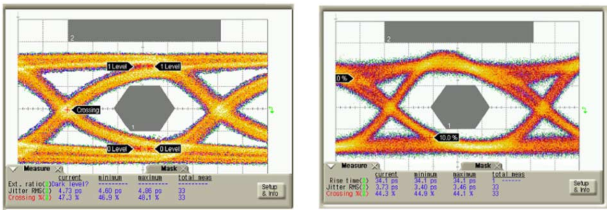

Fig. 4. (a) Eye pattern at 10 Gb/s received by the InGaAs PINPD without TIA. (b) Eye pattern at 10 Gb/s received by the InGaAs PINPD with TIA. (Color version available online at http://ieeexplore.ieee.org.)

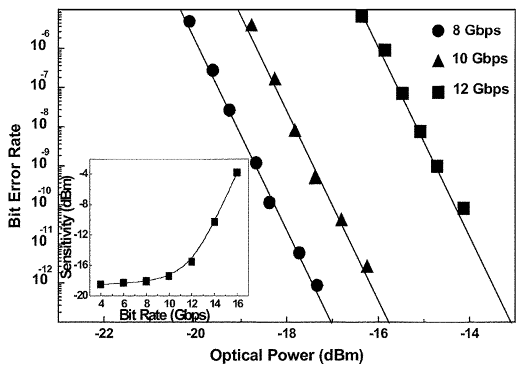

Fig. 5. BER analysis of InGaAs PINPD-TIA receiver at different data rates. The inset shows the measured sensitivity for a BER of less than 1×10^{-9}.

data stream received by the InGaAs MM-PINPD can be accurately calculated from the recorded Q-factor of the received eye pattern at a desired data rate. The equivalent mean and sigma of the marks and spaces are determined by fitting this data to Gaussian characteristic. As a result, the measured I_1, I_0, σ_1 and σ_0 are 13.9, 0.52, 0.75, and 0.88 mV, respectively, in our case. The measured Q-factor of such an optical receiver can be as high as 8.21, providing a reachable BER of 1.1×10^{-16} at the data rate of 10 Gb/s.

Finally, the BER measurement of the InGaAs MM-PINPD packaged with a TIA (Analog Device, ADN2821) were performed. At input optical power -6 dBm, the received eye diagram of a 10-Gb/s optical NRZ data stream at 1550 nm is shown in Fig. 4(b). Note that the overshoot and double-line phenomena occurred in the received eye pattern are partly due to the self-oscillation and the less flattened frequency response of the packaged MM-PINPD and TIA module. Although the reported optical responsivity of 0.6 A/W at 1550 nm is not a surprising result, the excellent performance in ultralow leakage and matched bandwidth of the proposed InGaAs MM-PINPD made on metamorphic InGaP buffered GaAs are the main benefits for receiving the SONET/SDH protocol at a bit rate up to 12 Gb/s. The inset of Fig. 5 illustrates that the measured sensitivity of the MM-PINPD at a BER of 1×10^{-9} degrades exponentially as the receiving data rate increases. For instance, the sensitivities of -18.8, -17.8, and -16.4 dBm corresponding to a BER of 10^{-9} are observed at data rates of 8, 10, and 12 Gb/s, respectively, as shown in Fig. 5. At beyond 10 Gb/s, the sensitivity degradation is due to the finite gain of the receiver limited by the *RC* time constants of the photodiode capacitance, the amplifier input capacitance, and the feedback resistance within the transimpedance preamplifier stage. The maximum operating speed can be adjusted up to 16 Gb/s with sensitivity of -3.9 dBm. These results again reflected that reducing the leakage current is a decisive way to improve the sensitivity of MM-PINPD owing to the significant suppression on the noise equivalent power of the receiver module. Temporal and eye diagram analyses of the received PRBS data corroborate that such a cost-effect InGaAs MM-PINPD on GaAs substrate guaranteed to be applicable in SONET OC-192 fiber-optic communication systems.

IV. Conclusion

We have demonstrated the SONET OC-192 receiving performance of a low-leakage $In_{0.53}Ga_{0.47}As$ p-i-n photodetector fabricated on semi-insulating GaAs substrate with a linearly graded metamorphic $In_xGa_{1-x}P$ buffer layer. Such a device exhibits an ultralow dark current density of 3.6×10^{-7} A/cm^2 at a bias of -5 V due to the excellent lattice grading characteristics of the metamorphic InGaP buffered layer between the InGaAs and GaAs matrices. The optical responsivity, switching response, and 3-dB frequency bandwidth are determined as 0.6 A/W, 41 ps, and 8 GHz. These parameters can be comparable to or even better than those of similar InGaAs MM-PINPD devices made on InGaAlAs buffered GaAs substrate. With a standard TO-46 package, the sensitivity of the MM-PINPD packaged with TIA at a date rate of 10 Gb/s and BER of 10^{-9} can be as low as -17.8 dBm. These results indicate that the demonstrated metamorphic InGaP epitaxy is a potential candidate to the mass-production of InGaAs MM-PINPDs on GaAs substrate for cost-effective TO-46 packaged OC-192 optical receivers.

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