40Gbps Waveguide Photodiodes

By Kikuo MAKITA,* Takeshi NAKATA,* Kazuhiro SHIBA* and Takeshi TAKEUCHI†

ABSTRACT Two types of waveguide photodiodes (WG-PD) — an evanescently coupled photodiode (EC-WG-PD) and a separated-absorption-and-multiplication avalanche photodiode (WG-APD) — were developed for use in 40Gbps receivers. The EC-WG-PD is much more robust than a conventional WG-PD under high optical input operation because of its distributed absorbed optical power density along the light propagation in the waveguide. The EC-WG-PD simultaneously exhibited a high external quantum efficiency of 70% for both 1,310 and 1,550nm, a wide bandwidth of >40GHz, and as high as 10mA photocurrent operation. The WG-APD, on the other hand, has a wide bandwidth of 35GHz and a gain-bandwidth product of 140GHz as a result of its small waveguide mesa structure and a thin multiplication layer. Record high receiver sensitivities of –19.6dBm at 40Gbps were achieved.

KEYWORDS **Photodiode (PD), PIN-PD, Avalanche photodiode (APD), Receiver, Evanescently coupled photodiode, Waveguide photodiode**

1. INTRODUCTION

The expansion of Internet traffic has created great demand for increased transmission capacity in fiber optic networks and for a boost in the transmission speed, from 10 to 40Gbps. To make 40Gbps transmission systems cost-effective and practical, high performance receivers operating at this speed are needed. Wideband, high-efficiency photodiodes (PDs) are key components of such receivers. An edge-illuminated waveguide configuration[1-4] has proven to be attractive for 40Gbps operation because it permits thinning the absorption region to reduce the carrier transit time without compromising efficiency. High receiver sensitivity has been achieved by using PIN-PDs with erbium-doped fiber pre-amplifiers (EDFAs). Since the PD is installed at the rear of the EDFA, the optical input power to the PD is normally several milliwatts high. In conventional PDs, the high speed response deteriorates at such a high input power level as a result of the space charge effect — the electric field lowering induced by photo-generated carriers. To suppress the space charge effect, we developed a wide bandwidth, high efficiency evanescently coupled waveguide photodiode (EC-WG-PD)[5] that is robust with regard to high input power. The EC-WG-PDs achieved a high external quantum efficiency of 65% for 1,310nm and 74% for 1,550nm. The 3dB-down bandwidth was as wide as 41GHz with 50Ω load resistance. These EC-WG-PDs can be applied in high-capacity long haul and in very-short-reach (VSR) transmission systems.

Avalanche photodiodes (APDs), on the other hand, are attractive and preferable for metropolitan networks because their internal gain enables receiver sensitivity higher than that of PIN-PDs. Moreover, APDs serve as compact, low-power-consumption receiver modules. For 40Gbps applications, the key issues for achieving high-sensitivity APDs are a wide bandwidth, high external responsivity, and a high-gain bandwidth (GB) product. Like the PIN-PDs, the edge-illuminated waveguide structure has attracted much attention, and it is capable of a wide bandwidth. We have developed AlInAs/GaInAs waveguide avalanche photodiodes (WG-APDs)[6] by implementing a small mesa structure and a thin (0.1μm thick) multiplication layer for application in 40Gbps receivers. These WG-APDs have a wide bandwidth of 35GHz, an external responsivity of over 70%, and a GB product of 140GHz.

2. EVANESCENTLY COUPLED WAVEGUIDE PHOTODIODES

2.1 Device Structure and Fabrication Process

Figure 1 shows the basic device structure and photocurrent density distribution calculated using the beam propagation method (BPM) for a conventional

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edge-illuminated WG-PD and an EC-WG-PD. A higher photocurrent density causes degradation in the frequency response due to the space charge effect and may damage the input facet. In a WG-PD, the input light is directly focused on the edge of a GaInAs absorption layer, and it is absorbed there in a concentrated manner. In an EC-WG-PD, the GaInAs absorption layer is partly loaded on an AlGaInAs passive waveguide layer. The input light is focused at the edge of the AlGaInAs passive waveguide layer and gradually penetrates to the absorption layer. This disperses the photocurrent density in the absorption layer, reducing it by roughly half that of the WG-PD. This suggests that the EC-WG-PD would be more robust than the WG-PD under high input power operation.

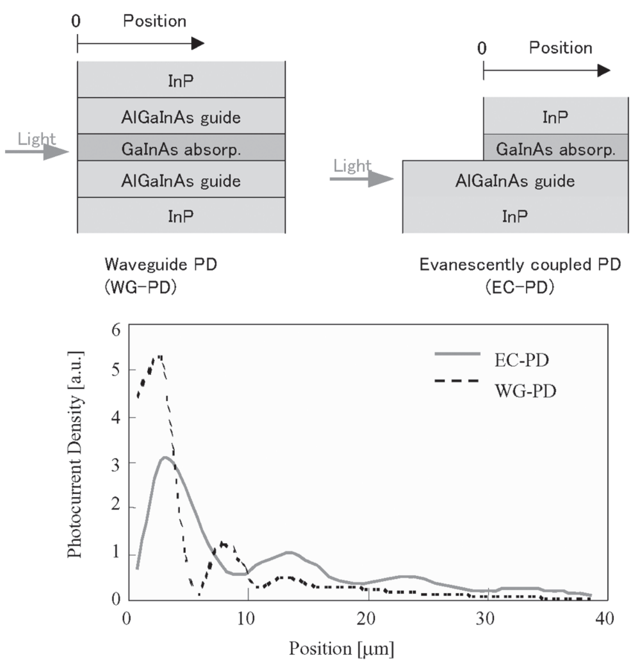

Fig. 1 Comparison between waveguide and evanescently-coupled PDs. (Top) Schematic structure and (Bottom) Photocurrent density distribution.

A schematic structure of the EC-WG-PD is shown in **Fig. 2**. All the semiconductor layers were grown using gas-source molecular beam epitaxy (GS-MBE) on a semi-insulating InP substrate. The distinctive feature of the EC-WG-PD is the thick graded-index optical waveguide layer. The refractive index of the graded-index optical waveguide layer increases layer by layer toward the absorption layer. The waveguide layer is composed of AlGaInAs (or InGaAsP) layers with a compositional wavelength of less than 1,200nm to reduce propagation loss over a wide wavelength range, from 1,310 to 1,550nm. The thickness of the waveguide layer is an essential design parameter to maximize the efficiency. The maximum photocurrent density monotonically decreases as the guide thickness increases, which means the optical intensity further distributes along the absorption region. However, the thicker waveguide makes the efficiency small because of a reduction in the optical penetration toward the absorption region. The waveguide thickness was designed to be 2.5 - 3.0μm because of this trade-off relationship. An integrated spot-size converter was introduced to increase fiber-coupling

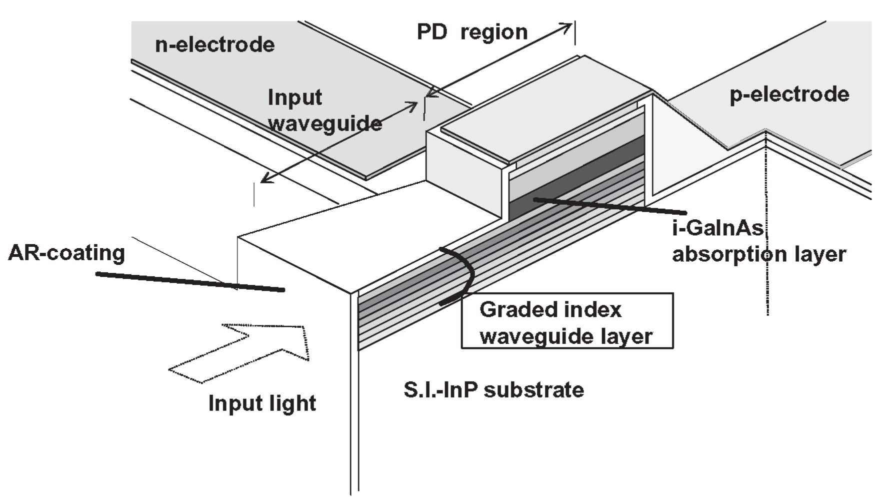

Fig. 2 Schematic structure of evanescently coupled waveguide photodiode (EC-WG-PD) with graded-index waveguide.

efficiency and its alignment tolerance. The loaded GaInAs absorption layer was also designed to achieve a high 3dB-down bandwidth of 40GHz in consideration of a CR time constant and carrier transit time limits. The undoped GaInAs absorption layer was 0.5μm thick. The PD region was 4μm wide and 30μm long. The input waveguide was as short as 20μm to reduce propagation loss. An anti-reflective SiNx coating was also formed on a cleaved facet of the graded-index waveguide using plasma enhanced CVD. The mesa structure was fabricated using a low-damage dry etching process, which made the mesa side-wall sharp and smooth. This fabrication process provides good uniformity and reproducibility, making cost-effective mass production possible.

2.2 Characteristics

The measured external quantum efficiencies are plotted in **Fig. 3**. A semispherical-ended single-mode fiber (SMF) was coupled to the graded index waveguide. A fabricated EC-WG-PD with a 30μm long absorption region achieved a high external quantum efficiency of 65% for 1,310nm and 74% for 1,550nm. The measured external quantum efficiency was less than the calculated results because of external fiber-coupling loss. The polarization dependent loss (PDL) was less than 0.2dB.

The frequency responses for average photocurrents up to 10mA were measured using an optical component analyzer with an erbium-doped fiber pre-amplifier. **Figure 4** shows the measured frequency responses. The 3dB-down bandwidth was 41GHz at an average photocurrent of 1mA, and it was 35GHz at 10mA. The loaded resistance was 50Ω, and the bias was 4V. The EC-WG-PD maintained high-speed performance under high input power, owing to a reduction in the space charge effect. In addition, we observed a clearly eye-opened waveform at 40Gbps for an implemented single-output receiver module. The module included an InGaP/GaAs hetero-junction transimpedance amplifier (TIA) IC. A 3dB-down bandwidth of 37.5GHz was achieved with this module[7]. This performance indicates the module is suitable for 40Gbps applications.

The device must be highly reliable for practical use. **Figure 5** shows a preliminary aging test under photo-illumination with a photocurrent of 3 to 5mA at 85°C and a bias of 3mA to 5V. The dark current was measured at room temperature. No significant degradation in dark current was observed over more than 11,000 hours of stressed operation. We also experimentally evaluated the maximum input power level

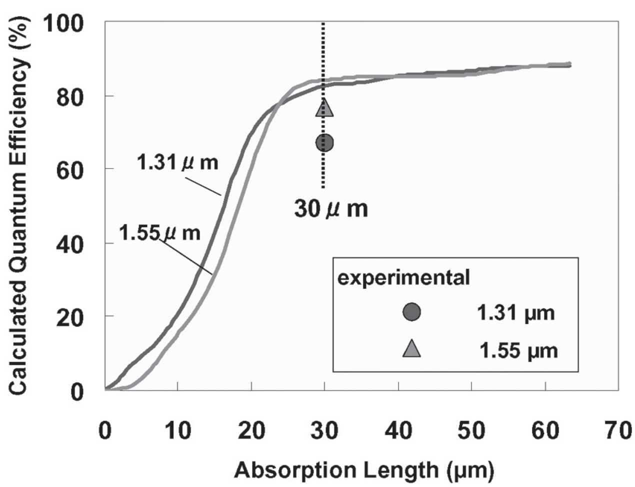

Fig. 3 Quantum efficiency for absorption region.

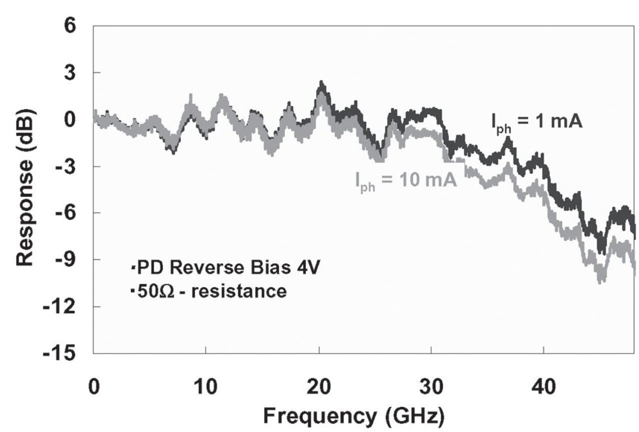

Fig. 4 Frequency response characteristics of EC-WG-PD at high input power.

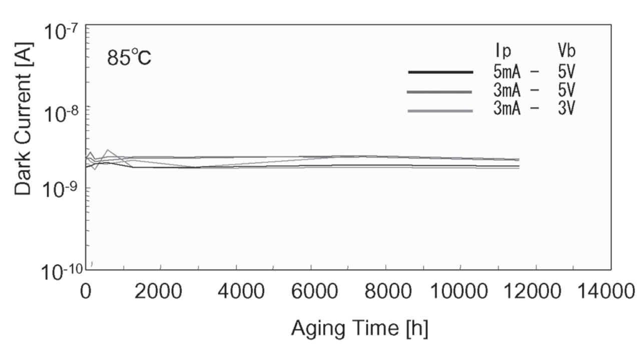

Fig. 5 Aging test under photo-illumination with photocurrent of 3 - 5mA at 85°C and bias of 3 - 5V.

at which catastrophic damage occurs. For the EC-WG-PDs, it was more than 21mW, making it approximately twice as robust as conventional WG-PDs under high input power operation.

3. WAVEGUIDE AVALANCHE PHOTODIODES

3.1 Device Structure and Fabrication Process

The APD structure widely deployed in fiber-optic detectors consists of separated absorption and multiplication regions (SAM), as schematically shown in **Fig. 6**. The structure consists of a wide-bandgap multiplication layer and a narrow-bandgap absorption layer separated by a field-buffer layer that exactly controls the electric field distribution for the SAM structure. Photons are absorbed in the absorption layer, and photo-generated primary electrons or holes are then injected into the multiplication layer to generate secondary electron-hole pairs. The avalanche time must be reduced to increase the bandwidth of the SAM-APD. The avalanche time τ_{av} appears to be the next relational expression for the multiplication factor M.

$$\tau_{av} \propto (kW/v_S)M \qquad (0<k<1) \qquad (1)$$

In this formula, k ($k = \beta/\alpha$) is the ionization rate ratio[8], where β and α are the hole and electron ionization coefficients, respectively. V_s is the saturation velocity of photo carriers. W is the multiplication layer thickness. The ionization rate ratio should be small to obtain high speed characteristics. However, it is essentially limited by the multiplication layer material. Furthermore, the multiplication layer should be as thin as possible to minimize the carrier transit time. However, the minimum value to which the multiplication region can be scaled down is ultimately determined by the onset of tunneling[9], which will result in excessive dark currents and degraded receiver sensitivity.

A schematic view of the WG-APD is shown in **Fig. 7**. The APD epi-wafers were grown on semi-insulating InP substrates by GS-MBE. The GS-MBE growth ensures well-defined heterostructures, which are essential for tailoring the electric field profile of the APD. The waveguide structure consists of an AlInAs/GaInAs SAM configuration as a core region sandwiched with upper p^+- and lower n^+-AlGaInAs (E_g: 1.3μm) optical guiding layers. The multiplication layer was adjusted to be thinned to 0.1μm under the trade-off relationship between the bandwidth and the dark current. A 0.02μm-thick p^+-AlInAs field buffer layer was incorporated between the 0.1μm-thick i-AlInAs multiplication layer and the 0.5μm-thick p^--GaInAs absorption layer to make the desired electric field distribution. The optical guiding layers were designed to be 0.7μm thick by using a beam-propagation method so as to obtain sufficient multi-mode coupling efficiency. Waveguide mesas with a width of 6μm and a length of 20μm were fabricated by inductively-coupled-plasma reactive-ion etching (ICP-RIE) and chemical wet-etching. The mesa edges were passivated with a SiN dielectric film.

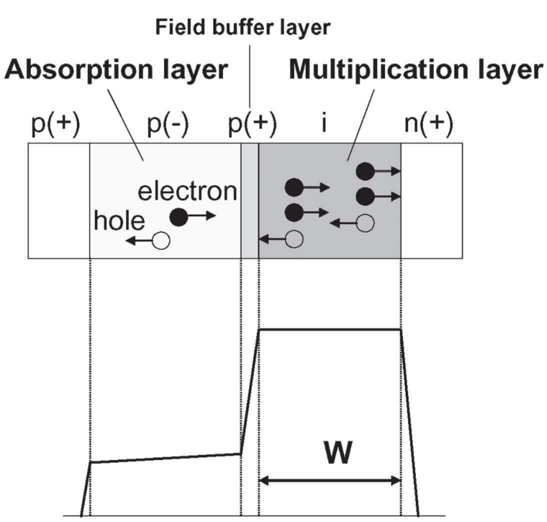

Fig. 6 Schematic diagram of separated absorption and multiplication (SAM) APD structure.

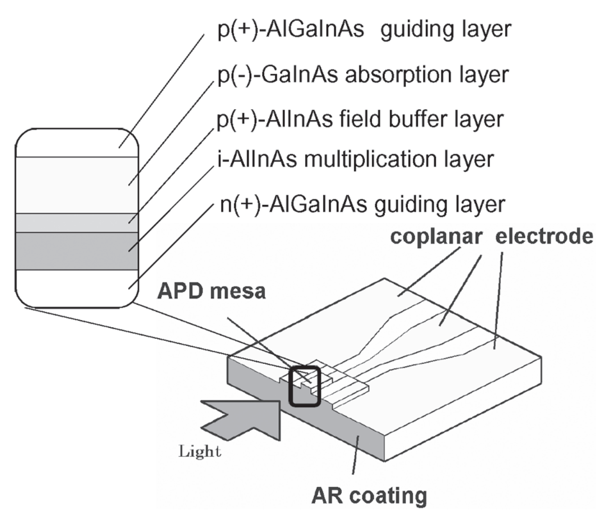

Fig. 7 Schematic view of separated absorption and multiplication waveguide avalanche photodiode (WG-APD).

3.2 Characteristics

Figure 8 shows the typical V-I characteristics of the WG-APD. The punch-through, the voltage at which the depletion reaches the absorption layer, was –7V, and the breakdown voltage was –16V. After the punch-through, a gradual increase in photocurrent gain was observed as the electric field increased in both the absorption and multiplication layers (between –7 and –16V). The unity gain is defined as a plateau level in the photo-response curve (–4 to –6V). We estimated the external responsivity was as high as 70% at 1.55μm by measuring the photocurrent at the plateau and incident light power with a 1.55μm wavelength. The junction capacitance was 20 - 30fF, and the series resistance was 10Ω.

The 3dB bandwidth at various gains (multiplication factors) is shown in **Fig. 9**. The maximum bandwidth of 35GHz at gains of two to three, which is the highest yet reported, was mainly limited by the CR time constant. At a higher gain, the bandwidth decreased as the gain increased so as to maintain a constant gain-bandwidth product (GB-product) that was limited by the avalanche time. The GB-product was 140GHz.

We tested the receiver sensitivity at 40Gbps. The maximum bandwidth of a WG-APD receiver including a TIA designed for 40Gbps operation was 27-28GHz at gains of 3. The receiver had a bandwidth of 27GHz at a multiplication factor of 10, owing to a TIA gain peak tuning at about 25GHz. The receiver sensitivity was measured using non-return-to-zero (NRZ) and a pseudo-random-bit-stream (PRBS) length of 2^7–1 at 40Gbps. **Figure 10** shows the results of a BER (Bit Error Rate) measurement and eye-patterns for the APD receiver. A clear eye-opening was obtained at a multiplication factor of 10. The minimum received power was as low as –19.6dBm at a BER of 10^{-9} and –19.0dBm at a BER of 10^{-10}. Again to the best of our knowledge, this is the first time 40Gbps operation using an APD receiver has been achieved, and this is the highest sensitivity yet reported for a receiver not employing a fiber pre-amplifier.

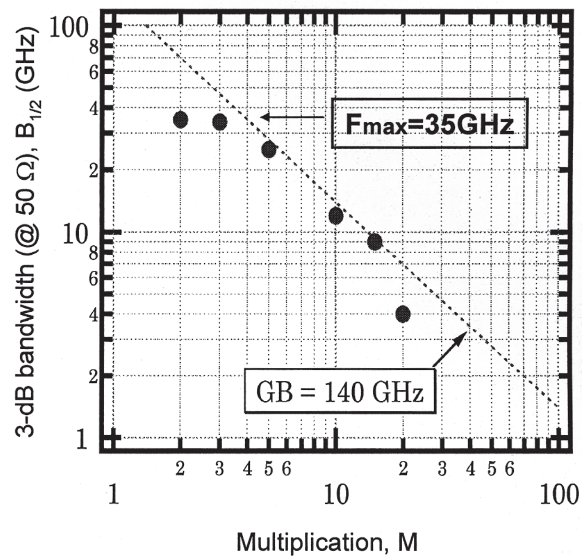

Fig. 9 Frequency response as a function of multiplication factor.

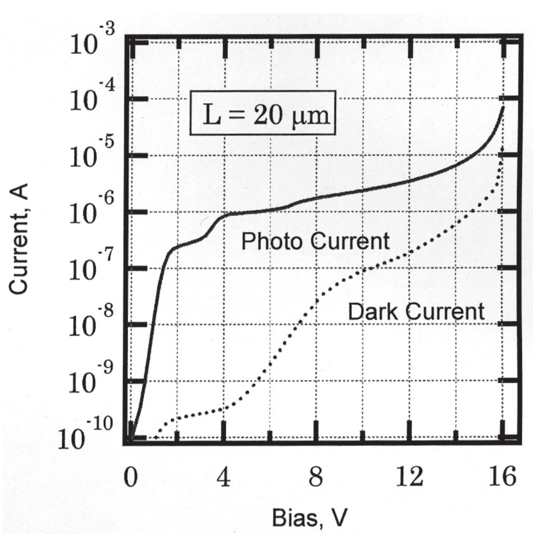

Fig. 8 Voltage/photocurrent characteristics of WG-APD.

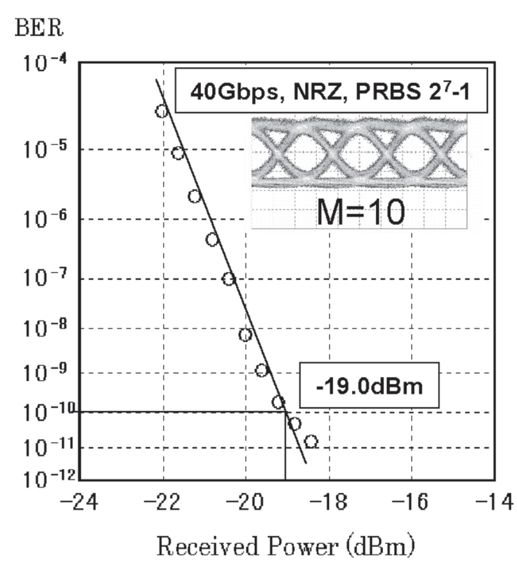

Fig. 10 Back-to-back receiver sensitivity for WG-APD measured at 40Gbps. Insert: eye diagram- Measured at 40Gbps.

4. CONCLUSION

We developed two types of wide bandwidth, high efficiency waveguide photodiodes for use in 40Gbps receivers. These were an EC-WG-PD and a separated-absorption-and-multiplication WG-APD. The EC-WG-PD is suitable for use in combination with EDFAs because an EC-WG-PD is more robust in terms of high input power than conventional edge-illuminated WG-PDs. The EC-WG-PDs achieved a high external quantum efficiency of 65% for 1,310nm and 74% for 1,550nm while maintaining a wide bandwidth of more than 40GHz. We also presented AlInAs/GaInAs WG-APDs as candidates for use in 40Gbps optical transmission systems. The maximum GB-product of our test was 140GHz, and it had a maximum bandwidth of 35GHz. The developed APD has a minimum received power of –19.6dBm at 40Gbps. As far as we know, these values are the highest sensitivities yet reported for long-wavelength APDs. These developed high-sensitivity optical receivers provide a compact, low-power-consumption option for high-bit-rate communication systems with moderate link lengths such as VSR and metropolitan networks.

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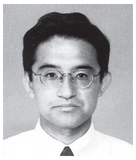

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