Design and Demonstration of High-Power and High-Speed Evanescently Coupled Photodiodes with Partially p-Doped Photo-absorption Layer

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Abstract: An evanescently-coupled-photodiode with partially p-doped photo-absorption layer was demonstrated and designed by a bandwidth simulation model to optimize its speed performance. Excellent performance of speed, saturation-power, and responsivity can be achieved simultaneously at 1.55μm wavelength.

OCIS codes: (230.5160) Photodetectors; (230.5170) Photodiodes; (230.7370) Waveguides

I. Introduction

The performance of microwave and millimeter-wave photonic systems would benefit from the use of photodetectors (PDs) with high power and high speed performance [1]. In order to release the trade-off between electrical bandwidth and power performance of high-speed PDs, Uni-travelling-carrier PDs (UTC-PDs) with ultra-high speed and output saturation power, have been demonstrated [1]. However, the main disadvantage of UTC-PDs is its relative poor quantum efficiency compared with traditional p-i-n photodiode [1]. Recently, *Y. Muramoto* and *T. Ishibashi* have demonstrated a new photodiode design that combines the depleted and neutral absorption layers (p-type doping) to maximize the bandwidth-efficiency product of photodiode [2]. Excellent performance has been demonstrated by use of such technique with the structure of vertical-illuminated PD. In this work, we incorporated the partially p-doped photo-absorption layer with the evanescently edge-coupled waveguide structure [3,4], which can uniform the distribution of photo-generated carriers along the optical waveguide and minimize the saturation problem in the front-end of edge-coupled photodiode [1,3,4]. Very high responsivity (1.01A/W), high electrical bandwidth (>50GHz), and high saturation power performances (over 6.5 dBm at 40GHz) have been achieved simultaneously at 1.55μm wavelength. A bandwidth simulation model has also been developed to optimize and analyze its high-speed performance under different levels of output photocurrent.

II. Design and Modeling of ECPD

In order to study the influence of partially p-doped photo-absorption layers on the high power performance of photodiode, two kinds of devices, which have the same structures of epi-layers except for the photo-absorption active region, were fabricated. Device A has the graded partially p-doped photo-absorption layer to accelerate the drift velocity of photo-generated electrons and device B has a pure intrinsic photo-absorption layer. The detail epi-layer and geometry structures of these two devices are give in Ref. [5]. An analytic bandwidth simulation model, which includes RC bandwidth limitation and nonlinear carrier transport effect, has been developed to optimize the structures of demonstrated photodiode for high speed performance. Eq. 1 and 2 is the transcendental equation for solving the net magnitude of electric field in the photo-absorption region and the drift velocity of photo-generated hole, respectively. The physical meanings and values of each parameter, which we used in bandwidth simulation, are given in Table 1.

$$E_{eff}=\left(\frac{\mathrm{V}_{bais}-Z_{load}\times J\times A+\mathrm{V}_{\mathrm{bi}}}{D}\right)-\left(\frac{J\times D}{\mathrm{V}_{\mathrm{hole}}\times\varepsilon}\right) \quad (1)$$

$$\mathrm{V}_{\mathrm{h}ole}=\mathrm{V}_{\mathrm{pl}}\times\tanh\left(\frac{\mu_h\times E_{eff}}{\mathrm{V}_{\mathrm{pl}}}\right) \quad (2)$$

By utilizing the solved drift velocity and a typical equivalent circuit model of p-i-n photodiode [6], we can obtain the simulated frequency responses, which are composed of carrier transport time and RC bandwidth limitation, under different output photocurrents (J). Fig.1 shows the simulated electrical bandwidth of the fabricated photodiodes versus the ratio of p-doped photo-absorption layer thickness to undoped photo-absorption layer thickness at a fixed absorption layer thickness (0.5 μm) under different output photocurrents.

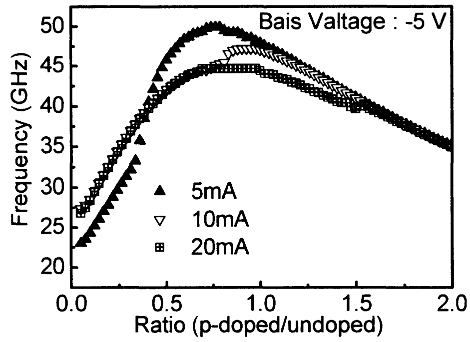

Fig. 1. The simulated electrical bandwidth vs. the ratio of p-doped photo-absorption layer thickness to undoped photo-absorption layer thickness under different operation current (5, 10, 20 mA). The thickness of InGaAs photo-absorption layer is fixed at 500nm.

Table 1. Symbols and quantities for equation (1)&(2)

Symbol	Quantity & Value
E_{eff}	Effective electric field intensity (V/m)
V_{bais}	Applied voltage (V)
A	Active area of photodiode
J	Generated current density (A/m^2)
V_{bi}	Built-in voltage of diode (0.7 V)
D	Depletion layer thickness(m)
ε	Dielectric Constant of InGaAs (1.23*10^{-10} F/m)
V_{hole}	Hole Velocity (m/s)
V_{pl}	Maximum Hole Velocity (4.8*10^4 m/s)
μ_h	Hole Mobility (60 cm^2/Vs)
Z_{load}	Load Impedance (50Ω)

We can clearly see that the partially p-doped technique, which shortens the depletion width (D) of photo-absorption layer, can improve the bandwidth performance significantly. According to the simulated results, we can thus choose the desired ratio of thickness (~0.7) to achieve near 50GHz electrical bandwidth performance under 5mA current operation.

III.Measurement Result:

We employed a tunable semiconductor laser as the light source for the dc photocurrent measurement. The center wavelength of this laser was fixed at 1550nm during the dc measurement. The measured devices A and B have similar geometry sizes and exhibit almost the same values of responsivity [5]. When the absorption length of device A is over 20μm (active area is larger than 150μm^2), a very high responsivity (1.01A/W) can be achieved. These results indicate that the partially p-doped photo-absorption layer of our structure will not degrade the performance of quantum efficiency. As compared with the reported responsivity of the evanescently coupled photodiodes with an integrated taper, the responsivity of our structure is significant higher due to much shorter coupling length (20 μm vs. 700 μm) and lower optical scattering loss of device [3]. The bandwidth and saturation current were measured with a heterodyne beating setup. Fig. 2 (a) and (b) show the measured and simulated frequency responses of device A and device B under a fixed dc bias (-5V) and different output photocurrent (0.05 mA, 2mA, and 5 mA), respectively. As the diagram indicates, the simulated traces fit well with the experimental results in both cases and device B with a thick intrinsic layer (D) thickness (500nm) will suffer from much serious bandwidth degradation phenomenon than device A.

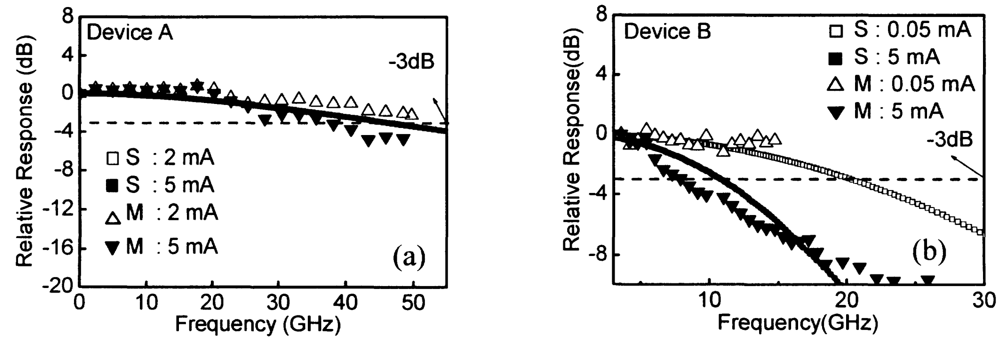

Fig.2 The comparison of measured (M) and simulated (S) frequency responses of device A (a) and device B (b) under different output photocurrent and a fixed dc bias voltage (-5V). The active areas of both devices are 200 μm^2.

The f_{3dB} electrical bandwidth of device A is over 50GHz under 2mA output photocurrent and it only slightly degrades to 40GHz when the output photocurrent increases to 5mA. The obtained high responsivity (1.01A/W) and high electrical bandwidth under high current operation (>50GHz at 2mA) of demonstrated device ensure its applications to 40Gbit/sec analog and digital fiber communication system.

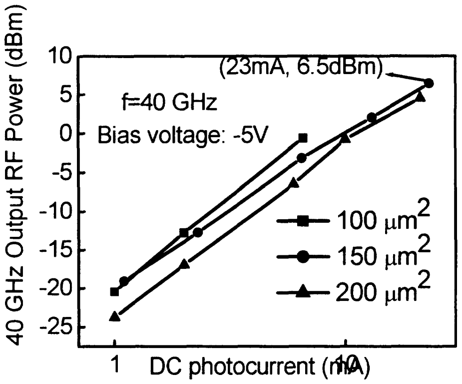

Fig. 2. RF power vs. dc photocurrent of ECPD with three different active area (100, 150, 200 μm^2) at 40GHz operating frequency. The maximum output current, power and the operation condition are indicated on the figure.

Three traces in Fig. 3 represent the photo-generated RF power versus dc photocurrent of device A with three different active areas ($100\mu m^2$, $150\mu m^2$, $200\mu m^2$). The operating frequency and dc bias voltage is fixed at 40GHz and -5V, respectively. The maximum value of RF generation power and DC photocurrent were indicated in the plot. As shown in this figure, the device with smallest geometry size ($100\mu m^2$) can have largest slope of photocurrent vs. RF power due to its smallest RC bandwidth limitation [7]. However, the maximum RF output power increases as the increase of active area of device. The observed phenomenon can be attributed to less density of photo-generated carriers and less space charge screening effect [7] of device with larger geometry size. The shown maximum RF output power of the three devices is limited by their failure. The obtained values of maximum power and current are much higher than the previous work on p-i-n evanescently coupled photodiodes with integrated tapers [1,3,4] at the same operating frequency (40GHz). To our knowledge, this is the highest saturation current and RF power (over 23mA vs. over 6.5dBm) reported with such a high responsivity (1.01A/W) and high electrical bandwidth (>50GHz).

IV.Summary:

We have demonstrated a novel ECPD to achieve high saturation photocurrent, responsivity, and large electrical bandwidth. The theoretical bandwidth simulation results reveal that the ECPD with partially p-doped photo-absorption layer offers fundamental advantages over traditional p-i-n photodiodes. By properly designing the epi-layer structures of demonstrated ECPD, sate of the art performances have been achieved: very high responsivity (1.01 A/W), broad bandwidth (>50 GHz), and over 23mA saturation current with corresponding 6.5dBm output RF power at 40GHz operating frequency.

V. Reference:

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