Photodiode with Partially Depleted Absorber, Leaky Optical Waveguide, and Distributed-Bragg-Reflector (DBR) for High-Power and High-Bandwidth-Responsivity Product Performance

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Abstract: We demonstrate a novel structure of photodiode. By incorporating the leaky optical waveguide with Distributed-Bragg-Reflector (DBR) and partially p-doped photo-absorption layer, this device exhibits much superior performance of speed, saturation power, and responsivity to the control without DBR mirrors.

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I. Introduction

The performance of microwave and millimeter-wave photonic systems would benefit from the use of photodiodes (PDs) with high saturation power, high-speed and high responsivity performance [1]. There are two major ways to satisfy these three requirements of PDs. One is to distribute and uniform the photocurrents along the edge-coupled PDs by improving the structure of optical and electrical waveguides, such as, velocity matched distributed photodetector (VMDP) with leaky optical waveguide [2] and evanescent coupled photodiode (ECPD) [3-5]; the other is to minimize the space-charge effect by changing the structure of epitaxial layers, such as uni-traveling carrier PD [1] and partially depleted absorber PD [6]. Recently, several research groups have demonstrated state-of-the-art performance of evanescent coupled PD with a short coupling length (~20μm) and partially depleted absorber [4,5]. However, the tolerance of cleaving process of such devices is very small (less than 5μm) and different length of coupling region will affect the responsivity performance seriously. For the case of PD with leaky optical waveguide, the problem of cleaving tolerance can be released greatly [2], but its electrical bandwidth is sacrificed for high responsivity performance due to that large device-absorption-volume is required to completely absorb the diluted optical power. In this paper, we demonstrate a novel structure of PD, which is composed of a leaky optical waveguide and distributed-bragg-reflector (DBR). By incorporating such novel structure with partially depleted absorber, the demonstrated device can achieve much superior performance of speed, saturation power, and responsivity to the control without DBR mirrors.

II. Device Structure

Figure 1 shows the cross-sectional view, top-view, and fabricated DBR mirror of demonstrated device. The period of DBR mirrors, which is labeled on the figure, is designed to have a maximum reflection at around 1550nm wavelength regime and fabricated by the e-beam lithography technique. The used leaky optical waveguide is composed of the two bottom undoped InGaAsP core layers (In0.9Ga0.1As0.21P0.79 2.5μm and In0.68Ga0.32As0.69P0.31 0.65μm), a thin heavily doped n-type InP etching stop layer, a In0.53Ga0.47As based photo-absorption layer with 0.3μm undoped and 0.2μm p-doped layer thickness, and topmost p-type InP cladding layer with 0.5μm thickness. The partially p-doped photo-absorption layer will shorten the depletion layer thickness and increase the saturation current of PD significantly [4,6]. After cleaving the device, an antireflection (AR) coating was deposited on the facet. The fabricated devices were integrated with the Co-Planar Waveguide (CPW) for on-wafer high-speed measurement. As shown in Figure 1, the shape of adopted CPW is twisted to avoid the contact with DBR region and excess optical scattering loss. As compared to the epi-layer structure of reported evanescent coupled photodiode [3-5], our demonstrated structure is much simpler and has much less numbers of epi-layer. According to our optical simulation, the required device-absorption-length of our structure without DBR mirrors is over 100μm, which will result in an electrical bandwidth performance (<10GHz) much less than 40GHz. By incorporating the high reflective DBR mirror with our leaky optical waveguide, the required absorption-length can be shortened due to that the optical path of injected beam is folded, and superior bandwidth-responsivity product performance can thus be
expected. Furthermore, due to the existence of DBR mirror, we can let the optical absorption process in our structure become more diluted and uniform compared with that of traditional leaky optical waveguide PD, which has the same active area and desired electrical bandwidth performance. Superior saturation current-bandwidth product performance of our novel structure can thus be expected.

III. Measurement Result:

In order to study the influence of DBR mirrors on device performance, we have fabricated the control-device without DBR mirrors. Both devices have similar epi-layer and geometry structure. We employed a tunable semiconductor laser as the light source for the dc photocurrent measurement. Figure 2 shows the measured responsivity under 1550nm optical pumping wavelength vs. different lengths of active diode with the same 5μm waveguide width and dc bias voltage (-3V). The measured polarization dependence of both devices is less than ±0.3dB. We can clearly see the devices with DBR mirrors can have significant higher responsivity than that of control-device with similar active length. For the device with DBR mirror and 32μm active length, the achieved responsivity is as high as 0.9A/W. Furthermore, our demonstrated device doesn’t exhibit serious wavelength selectivity, which is serious for resonant-cavity-enhanced PD (RCEPD) [7], due to its much longer cavity length and an AR coating was applied on the input facet. The obtained responsivities of both devices don’t change when the pumping wavelength varied from 1485nm to 1570nm. The bandwidth and saturation current were measured with a heterodyne beating setup. Figure 3 shows the measured frequency responses of both device with different active areas and almost similar responsivity performance (0.9 vs. 0.8A/W). The measured conditions are also labeled on this figure. Compared with the control-device, the device with DBR mirrors can not only have much higher electrical bandwidth performance (~37GHz vs. ~17GHz) due to its smaller geometry size but also much higher bandwidth responsivity product (33.3GHz-A/W vs. 13.3GHz-A/W). Figure 4 shows the measured frequency response of the same device with DBR mirror under different bias (-3V and -1V) and a fixed 15mA output photocurrent. Even under such high output photocurrent, an around 40GHz electrical bandwidth (~37GHz) has been achieved under -3V bias. The obtained high responsivity (0.9A/W) and high electrical bandwidth under high current operation (~37GHz at 15mA) of demonstrated device ensure its applications to 40Gbit/sec analog and digital fiber communication system. Two traces in Fig. 5 represent the photo-generated RF power of device with DBR mirror versus dc photocurrent under two different bias voltages (-1V and -3V). The operating frequency is fixed at 40GHz. The ideal relation between RF power of a 100% modulated large-signal and the average current on a 50Ω load is also plotted as straight line for reference. The obtained values of saturation power (~5dBm) and photocurrent current (~18mA) are much higher than the previous work on p-i-n evanescent coupled photodiodes [3]. Furthermore, as compared to state-of-the-art performances of reported evanescent coupled PD with partially p-doped absorber [5], our demonstrated device can have comparable electrical bandwidth (~40GHz vs. 50GHz), responsivity (0.9A/W vs. 0.81A/W) and saturation current performance (18mA vs. 17mA).

IV. Summary:

We have demonstrated a novel structure of PD at 1.55μm wavelength. By combing the DBR mirrors with leaky optical waveguide structure, such device exhibits superior performance of speed, responsivity, and saturation current to control-device. As compared to the reported results of state-of-the-art evanescent coupled PD, our device can not only have much larger tolerance of cleaving process but also comparable excellent performance.
Figure 2. Responsivity versus different length of active diodes with and without DBR mirrors. The bias voltage of this measurement is fixed at -3V.

Figure 3. The measured frequency responses of both devices under a fixed dc bias voltage (-3V) and output photocurrent (5mA) (square: device with DBR mirror, circle: device without DBR mirror). The active area of device with and without DBR is 160μm² and 260μm², respectively.

Figure 4. The measured frequency response of device with DBR mirror under a fixed output photocurrent (15mA) and different bias voltages (square: -1V, circle: -3V).

Figure 5. RF output power of device with 160μm² active area versus photocurrent at 40GHz under -1V (square) and -3V (circle) bias. The ideal relation between RF power and current on a 50Ω load is plotted as the straight line (triangle) for reference.

V. Reference:


