

High Focusing-reflection Subwavelength Gratings with Uni-traveling-carrier Photodetector for High Responsivity

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Abstract

High focusing-reflection, non-periodic high-contrast grating integrated with a uni-traveling-carrier photodetector (FR-UTC-PD) is proposed to overcome the bandwidth-responsivity trade-off. The responsivity of the FR-UTC-PD is increased by 36.5% while achieving a 3-dB bandwidth of 18 GHz.

Full Text

Preamble

High Focusing-reflection Subwavelength Gratings with Uni-traveling-carrier Photodetector for High Responsivity

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Abstract: A high focusing-reflection, non-periodic high-contrast grating integrated with a uni-traveling-carrier photodetector (FR-UTC-PD) is proposed to overcome the bandwidth-responsivity trade-off. The responsivity of the FR-UTC-PD is increased by 36.5% while achieving a 3-dB bandwidth of 18 GHz. ©

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1. Introduction

Single-layer, high-index contrast subwavelength grating structures—commonly known as high-contrast gratings (HCGs) with distinct constructed forms—can provide high focusing-reflection (FR), high transmission, and high-quality-factor resonances. These structures have been extensively applied in the integration of various optoelectronic devices, including vertical-cavity surface-emitting lasers (VCSELs), tunable VCSELs, sensors, resonators, and hollow-core waveguides [1]. Moreover, periodic or non-periodic concentric-circular subwavelength gratings serving as focusing reflectors have made significant contributions to improving photodetector (PD) responsivity without sacrificing high-speed response [2].

The uni-traveling-carrier photodetector (UTC-PD) can achieve high-speed and high-saturation characteristics by employing only electrons as active carriers and utilizing a separated design for the absorption and collection layers [3-4]. Nevertheless, constraints remain among these characteristics, particularly in achieving simultaneously high responsivity and high bandwidth. Therefore, solving the bandwidth-responsivity trade-off in UTC-PDs is particularly important. Several monolithically or quasi-monolithically integrated structures, such as resonant-cavity-enhanced UTC-PD (RCE-UTC-PD) [5] and high-reflectivity UTC-PD (HR-UTC-PD) [6], have been proposed to improve UTC-PD responsivity. However, these approaches involve problems related to the time and cost of epitaxial growth for distributed Bragg reflectors (DBRs) and complexities in monolithically integrated PD fabrication.

In this paper, we report a high FR uni-traveling-carrier photodetector (FR-UTC-PD) structure that experimentally realizes the integration of a high FR non-periodic concentric circular high-contrast grating (NP-CC-HCG) mirror with a high-speed UTC-PD using wafer-bonding technology, thereby overcoming the bandwidth-responsivity trade-off in UTC-PDs. The schematic design is shown in Fig. 1(a).

2. Focusing-reflection Theory

The NP-CC-HCG mirror in an FR-UTC-PD consists of a set of concentric circular Si units with a thickness of 500 nm located on top of a silicon-on-insulator (SOI) substrate, as shown in Fig. 1(a). The high-index Si grating units surrounded by adjacent air and a 500-nm-thick bottom SiO₂ layer with low indices of 1 and 1.46 constitute a high-index contrast grating structure—namely, the NP-CC-HCG mirror [7]. A focusing spot of the reflected light can be obtained when the total phase shift satisfies Eq. (1) [1]:

$$\phi(x) = 2\pi \left(f + \frac{\phi_{\max}}{\lambda} - \sqrt{x^2 + f^2} \right) \quad (1)$$

where f is the focal length, λ is the wavelength, x is the radius of an NP-CC-HCG mirror, and ϕ_{\max} is the maximum phase change.

To further analyze the FR ability, we calculated the ideal phase distribution of the NP-CC-HCG mirror with a focal length of 12 m using Eq. (1). The relevant simulation was implemented with 1550-nm radially polarized light, and the results are shown in Fig. 2(a). The discrete non-periodic concentric circular grating bars along the x direction coincide exactly with the theoretical calculation results. We evaluated the FR ability of the NP-CC-HCG mirror using COMSOL with the finite element method (FEM), as shown in Fig. 2(b). The focus spot along the z -axis occurs at 11.65 m, which is very close to the 12-m theoretical setting value. Additionally, the relevant field distribution full-width-half-maximum (FWHM) at the reflected focus plane is 0.8701 m, and a total FR efficiency of 92.1% is obtained at the reflected plane.

3. Results and Discussion

The UTC-PD structure on top of the NP-CC-HCG mirror mainly consists of a 640-nm-thick p-type InGaAs absorption layer and a 500-nm-thick n-type InP collection layer. The formation of a quasi-electric field in the absorption layer due to Gaussian-graded doping helps electrons diffuse or drift rapidly to the collection layer. An undoped InGaAsP layer is applied to smooth the abrupt InGaAs/InP heterojunction. The double-mesa structure with p- and n-type Ohmic contacts is fabricated using conventional photolithography and wet etching technologies. Ground-signal-ground (GSG) coplanar waveguide Ti/Au-contact electrodes are then landed on the surface of the polyimide passivation layer. After completing the UTC-PD fabrication, the InP substrate layer below the n-type InP buffer layer is first ground and then polished in preparation for wafer bonding with the NP-CC-HCG mirror.

Meanwhile, the 500- μ m-diameter NP-CC-HCG mirror with a focal length of 400 m is fabricated by E-beam lithography (EBL) and inductively coupled plasma (ICP) dry etching. SEM images at various locations are shown in Figs. 1(b) and 1(c). Figure 3 illustrates the FR ability of the NP-CC-HCG mirror, represented by the power distribution at the reflected focal plane. The measured results show that the reflected optical power approximately follows a Gaussian distribution along the x direction, with the peak power located at the middle position of the NP-CC-HCG mirror, demonstrating excellent focusing ability. Moreover, the maximum reflected optical power at the focal spot is 463.5 W, with a corresponding FWHM of \sim 140 μ m, while an FR efficiency of 84.59% is achieved by integration. Subsequently, the FR-UTC-PD is realized by wafer bonding the UTC-PD structure with the NP-CC-HCG mirror.

Figure 4(a) shows the measured DC saturation current for the UTC-PD and FR-UTC-PD under a bias voltage of -3.0 V and 1550-nm wavelength excitation. The linear regions show that output photocurrent gradually increases with input power until reaching a saturation point, revealing the device responsivity

characteristics. The relevant responsivity is 0.63 A/W and 0.86 A/W for the UTC-PD and FR-UTC-PD, respectively. Compared to the UTC-PD without the NP-CC-HCG mirror, the responsivity of the FR-UTC-PD is increased by 36.5%. This improvement occurs because the NP-CC-HCG mirror enables the FR-UTC-PD to achieve nearly twice the effective absorption efficiency from incident light compared to the UTC-PD. Moreover, the responsivity of the FR-UTC-PD could be further improved by optimally designing the focal length of the NP-CC-HCG mirror to ensure more reflected light is absorbed by the absorption layer.

Figure 4(b) shows the measured frequency response of the FR-UTC-PD and UTC-PD at various low output photocurrent levels. The 3-dB bandwidth for both devices is 18 GHz at a bias voltage of -3.0 V with a 1550-nm wavelength source. Therefore, the NP-CC-HCG mirror does not affect the bandwidth of the UTC-PD.

4. Conclusions

We report a high-performance FR-UTC-PD achieved by integrating an NP-CC-HCG mirror with a UTC-PD structure to overcome the trade-off between responsivity and bandwidth in UTC-PDs. The FR ability of an NP-CC-HCG mirror is analyzed theoretically, yielding a focal length of 11.65 μm . The field distribution FWHM at the reflected focal plane is 0.8701 μm , and the FR efficiency at the reflected plane is 92.1%. For a fabricated NP-CC-HCG mirror with a 400 μm focal length, the reflected optical power is 463.5 μW , the corresponding FWHM is ~ 140 μm , and the calculated FR efficiency is 84.59%, all achieved using 1550-nm wavelength radially polarized light. The FR-UTC-PD is realized using wafer bonding technology, achieving a responsivity of 0.86 A/W—representing a 36.5% improvement compared to a UTC-PD without an NP-CC-HCG mirror. The 3-dB bandwidth of the FR-UTC-PD is neither increased nor degraded relative to that of the UTC-PD without an NP-CC-HCG mirror.

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