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Responsivity Characteristics of InP/InGaAs Heterojunction Phototransistors with Strained InAs/InGaAs Multiquantum Well Absorption Layers

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1. Introduction

Mid-infrared photodetectors operating in the 2.0–2.4 μm wavelength region are very useful for trace-gas monitoring applications such as atmospheric pollution monitoring and atmospheric remote sensing. This is because CO_2 and N_2O exhibit strong absorption peaks and furthermore absorption by water vapor is very weak in this wavelength region. The mid-infrared photodetectors can be classified as photoconductive or photovoltaic detectors. The former has a low response speed, and the responsivity and response speed change with temperature. The latter has a fast response speed and a good signal-to-noise (S/N) ratio. However, narrow-bandgap-based detectors have a large dark current at room temperature (RT), and then, they generally require a cooling system.

In this paper, we describe a RT operative, high-responsivity heterojunction phototransistor (HPT) that amplifies the photocurrent from a strained InAs/InGaAs multiquantum well (MQW) absorption layer and reveals absorptions in the 2.0-μm wavelength region. The responsivity characteristics of HPTs with MQWs inserted in different regions such as the base and the collector are investigated.

2. Device structure

The designed HPT has an $In_{0.53}Ga_{0.47}As$ cap layer (0.02 μm, n = 5 × 10^{18} cm^{-3}), a wide bandgap InP emitter (0.5 μm, n = 1 × 10^{19} cm^{-3}+0.1 μm, n = 5 × 10^{17} cm^{-3}), an $In_{0.53}Ga_{0.47}As$ spacer (0.005 μm, undoped), an $In_{0.53}Ga_{0.47}As$ base (0.134 μm, p = 1 × 10^{18} cm^{-3}), an $In_{0.53}Ga_{0.47}As$ collector (0.2 μm, undoped), and an n-$In_{0.53}Ga_{0.47}As$ subcollector (0.02 μm, n = 3 × 10^{18} cm^{-3}) grown on n-type (100)-InP substrates. Because InAs has a large lattice mismatch with InP (3.2%), only a thin strained-epitaxial layer can be grown on InP. Therefore, we used a five-period strained InAs/$In_{0.53}Ga_{0.47}As$ MQW with 5-nm-thick InAs, which showed good photoluminescence (PL) characteristics [1], as an absorption layer inserted in the base or collector region. It can be used to detect wavelengths of up to 2.3 μm. The photogenerated current modulates the base potential, which is amplified by the current gain, resulting in high responsivity. The device has a ring-shaped emitter electrode on its top surface, which receives the incident light. No antireflection coating was used [2].

The MQW structure induces a large change in the optical properties due to the quantum-size effect, along with a strong excitonic effect as compared to that of a bulk semiconductor. The excitonic effects result in a considerable increase in the absorption coefficient in the vicinity of the absorption edge as compared to that of the bulk material. However, an electric field affects the absorption properties of the MQW, causing the absorption wavelength to expand; this phenomenon is called as the quantum confined Stark effect (QCSE). In the presence of an electric field, the wavefunctions have an oscillatory tail that extends out of the well, resulting in a reduced absorption peak caused by the field-induced broadening of the wavefunctions. On the other hand, although a low electric field allows for strong excitonic effects, the carrier escape is an issue to be noted. There is a difference between the electric field in the base and the collector, as schematically shown in Fig. 1. We investigate the effect of the electric field on the responsivity characteristics by inserting the MQWs either in the base or in the collector.

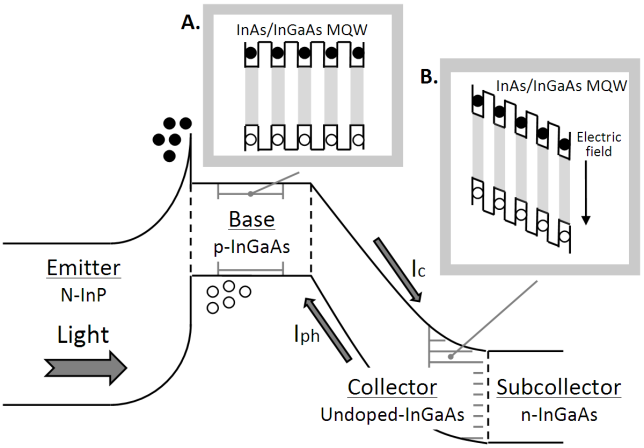

Fig. 1. Schematic band diagram.

3. Optical Characteristics

The wavelength dependence of the spectral response was measured by irradiating with light of 2.0–2.5 μm, which was outputted from a monochromator separating the light from the tungsten lamp. The measured responsivity dependence on the wavelength of the device with a 1-mm-diameter active region is shown in Fig. 2. The responsivity is 10.8 A/W at a wavelength of 2.345 μm for an HPT with MQWs inserted in the collector, while it is as low as 0.054 A/W at a wavelength of 2.2 μm for an HPT with MQWs inserted in the base. The wavelength giving peak responsivity in an HPT with MQWs inserted in the collector shifted toward a longer wavelength relative to that in an HPT with MQWs inserted in the base, and the large absorption peak was attributed to exciton formation. On the contrary, there is almost no exciton absorption in an HPT with MQWs inserted in the base. This is attributed to the quenching of excitons associated with the filled subbands

due to holes flowing from the p-base, i.e., the so-called phase-space filling effect [3].

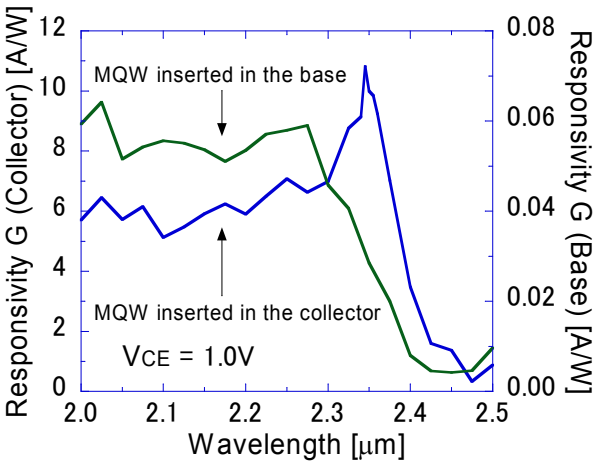

Fig. 2. Responsivity dependence on wavelength

4. Electrical Gain Characteristics

The electrical characteristics were measured at room temperature. Figure 3 shows the common-emitter current gain (β) characteristics of the device with a 250-μm-diameter active region operated in the heterojunction bipolar transistor mode, which means that the base current (I_b) was supplied through the base electrode. The current gain of an HPT with MQWs inserted in the collector is approximately 100 times larger than that of an HPT with MQWs inserted in the base. When the current gain is dominated by the carrier recombination in the base, current gain dependence on the collector current becomes weak, as is the case here. In such a case, the electron diffusion length (L_{nB}) in the base is given as follows [4]:

$$L_{nB} = \left(\frac{\beta \cdot W_B^2}{2} \right)^{\frac{1}{2}} \quad (1),$$

where W_B is the base thickness. For W_B of 0.134 μm, the calculated L_{nB} is 1.57 μm and 0.177 μm for HPTs with MQWs inserted in the collector and the base, respectively. The former is approximately ten times larger than the latter. For an HPT with MQWs inserted in the base, the carriers once captured in the wells cannot easily escape due to the low electric field, thereby resulting in low L_{nB}. This produces a large recombination current in the base, and this is responsible for the low current gain.

5. Discussion

The absorption efficiency (η) is calculated using Eq. (2) [5].

$$\eta = \frac{hc}{q\lambda} \cdot \frac{G}{\beta} \quad (2),$$

where h is the Planck constant; c, the speed of light; q, the elementary charge; λ, the wavelength, and G, the responsivity. η is related to the absorption coefficient (α) as follows [6]:

$$\eta = (1-R)(1-e^{-\alpha L}) \quad (3),$$

where R is the reflectivity at the incident surface and L, the absorption length.

The estimated α at a wavelength of 2.1 μm assuming R = 0.3 and L = 25 nm (which is the sum of the well thicknesses) is 1.02 and 0.61 μm^{-1} for HPTs with MQWs inserted in the collector and in the base, respectively. Because the generated carriers absorbed in the MQWs inserted in the base are not accelerated by the low electric field in the base, some of them recombine in the well. On the other hand, because the generated carriers absorbed in the MQWs inserted in the collector are accelerated by the collector electric field, most of them are subtracted from the MQWs. This is thought to be the reason for the smaller α values in the HPT with MQWs inserted in the base. In contrast, the estimated α at a wavelength of 2.345 μm is 1.95 and 0.30 μm^{-1} for HPTs with MQWs inserted in the collector and in the base, respectively; therefore, at this wavelength, there is a larger difference in α. For an HPT with MQWs inserted in the collector, α at a wavelength of 2.345 μm is 1.9 times larger than that at 2.1 μm. This larger α is attributed to enhanced absorption due to the excitons.

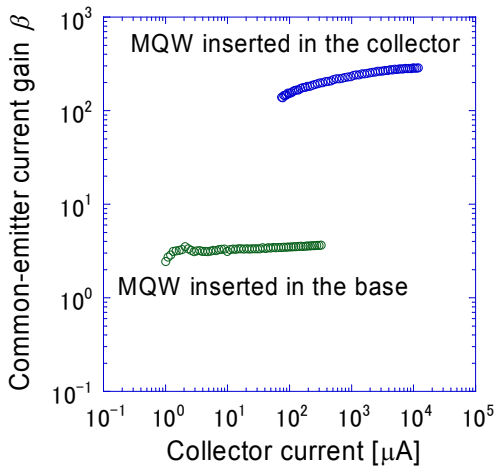

Fig. 3. Current gain characteristics.

6. Conclusion

In this study, we investigate the responsivity characteristics of HPTs with MQWs inserted in different regions such as the base and the collector. The effective diffusion length in the HPT with MQWs inserted in the collector becomes approximately ten times larger than that with MQWs inserted in the base, resulting in a large current gain. In addition, enhanced absorption coefficient due to the excitons is observed in the HPT with MQWs inserted in the collector. These two factors contribute to the high responsivity of the device with the MQWs inserted in the collector.

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