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Broadband staircase quantum well infrared photodetector with low dark current

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Abstract

We present a theoretical investigation of a novel staircase-like quantum well infrared photodetector (QWIP). It detects wavelengths between 8.8 μm and 12.3 μm at an applied electric field of $F = 6 \times 10^4$ V/cm at room temperature. Device operation is based on inter-subband bound to continuum transition. We also calculated the responsivity at room temperature and dark current density at 77 K. The dark current density was found to be around 10^{-8} A/cm^2 at operating bias, which is lower than the conventional QWIPs in the literature.

Keywords: Detector; QWIP; Absorption coefficient; Dark current density

1. Introduction

Infrared detection has been a key factor in the development of infrared technology during the past decade. Many materials including InSb and HgCdTe have been widely used in detector applications. However, due to the rapid development in material growth technology using molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), low dimensional structures such as superlattices and quantum well devices have been widely studied as infrared detectors. Quantum well infrared photodetectors (QWIPs) are one of the most important devices in infrared technology. The advantages of using QWIPs based on III–V compounds over conventional materials come from their mature growth and device processing capabilities. This leads to high uniformity, as well as excellent reproducibility and thus to large area, low-cost arrays. In addition, a more important advantage of QWIPs is the ability to accurately control the band gap, barrier and well widths and doping concentrations which permit monolithic multi-spectral infrared detectors and integration with other high speed devices [1]. All these advantages and technological needs make them desirable in applications, such as ultrahigh sensitivity gas sensing systems, infrared imaging applications, and other military technologies. A large number of sophisticated QWIP structures have, to date, been investigated. These include large area focal plane arrays [2]

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multicolor [3,4] and broadband detectors [5]. Based on inter-subband transitions, they have been used for detection in the 3–5 μm mid-wavelength infrared (MWIP) and 8–14 μm long-wavelength infrared (LWIP) atmospheric spectral windows [5–8].

Recently, we have proposed a single wavelength staircase-like detector working in long-wavelength atmospheric window which is based on bound-to-bound transition. The advantage of the staircase-like structure has been shown as low dark current density in the previous work of our group [9]. In this paper, we present a theoretical study of a broadband staircase infrared detector with low dark current density. The detector structure is sensitive to 8.8–12.3 μm spectral range at room temperature. The investigated optical transitions are inter-subband bound to continuum transitions. In the literature [5,6,10–13] bound-to-continuum QWIPs have dark current varying from 10^{-5} to 10^{-8} A at 77 K. Since the structure contains a wide right most barrier at operating bias the dark current density is decreased to 10^{-8} A/cm^2 at 77 K.

2. Device structure

The device structure, which we investigate, is a three-well system, consisting of quantum wells and barriers where x concentration varies from 0 to 0.45. The exact composition and the thickness of all quantum wells and barriers as well as the doping concentrations are given in Table 1. The resulting device parameters including the potentials are given in Table 2. $z_n^{\mathrm{b}}(z_n^{\mathrm{w}})$ shows the distance of the left hand side of the nth barrier (well) from origin. The doping concentrations of the two $n+$GaAs contact layers were chosen to be $1\times10^{18}\,\mathrm{cm}^{-3}$. Quantum wells were doped $N_{\mathrm{D}}=1\times10^{16}\,\mathrm{cm}^{-3}$ and barriers were undoped. This choice of the doping level not only avoids the band bending at opposite ends of the device but also allows for the formation of good ohmic contacts. The last barrier thickness has been chosen to be 170 A as seen from Fig. 1. Therefore, the electrons occupied at the ground state of the last quantum well will be prevented to escape.

Table 1
Summary of device structure

	Composition (x)	Thickness (A)	Doping
Emitter	0	10,000	$1\times10^{18}\,\mathrm{cm}^{-3}$
First barrier	0.25	35	Undoped
First well	0.1	40	$1\times10^{16}\,\mathrm{cm}^{-3}$
Second barrier	0.33	35	Undoped
Second well	0.167	45	$1\times10^{16}\,\mathrm{cm}^{-3}$
Third barrier	0.4	50	Undoped
Third well	0.25	55	$1\times10^{16}\,\mathrm{cm}^{-3}$
Fourth barrier	0.45	170	Undoped
Collector	0	10,000	$1\times10^{18}\,\mathrm{cm}^{-3}$

Table 2
Calculated potentials and widths for barriers (b) and wells (w)

n	$V_n^{\mathrm{b}}(V_n^{\mathrm{w}})$ (eV)	$z_n^{\mathrm{b}}(z_n^{\mathrm{w}})$ (A)
1	0.2 (0.08)	150 (185)
2	0.264 (0.1336)	225 (260)
3	0.32 (0.2)	305 (360)
4	0.36	410

3. Theoretical considerations

Potential energy of the system shown in Fig. 1 can be given as

$$V = V_G + V_{\max} \tag{1}$$

where

$$V_G = \sum_{n=1}^{3} V_G^n \tag{2}$$

$$V_{\max} = V_{\max} S(z - z_4^{\mathrm{b}}) \tag{3}$$

where S is the step function and

$$V_G^n = \begin{cases} V_n^{\mathrm{b}}, & Z_n^{\mathrm{b}} < Z < Z_n^{\mathrm{w}} \\ V_n^{\mathrm{w}}, & Z_n^{\mathrm{w}} < Z < Z_{n+1}^{\mathrm{b}}, \quad S \text{ is the step function} \\ 0, & \text{elsewhere} \end{cases} \tag{4}$$

Hamiltonian of the system can be written as

$$H = \frac{P^2}{2m} + V \tag{5}$$

Since the band bending of the structure can be omitted at steady state, eigenfunctions of the Hamiltonian in the wells and barriers are of the following form

$$\Psi_{\mathrm{well}} = A_n \mathrm{e}^{\mathrm{i}k_n^{\mathrm{w}} z} + B_n \mathrm{e}^{-\mathrm{i}k_n^{\mathrm{w}} z} \tag{6}$$

$$\Psi_{\mathrm{barrier}} = C_n \mathrm{e}^{k_n^{\mathrm{b}} z} + D_n \mathrm{e}^{-k_n^{\mathrm{b}} z} \tag{7}$$

Here the k_n^{w} and k_n^{b}, wave numbers of wells and barriers, for the effective mass approximation, are

$$k_n^{\mathrm{w}} = \sqrt{\frac{2m^*}{\hbar^2}(E - V_n^{\mathrm{w}})} \tag{8}$$

$$k_n^{\mathrm{b}} = \sqrt{\frac{2m^*}{\hbar^2}(V_n^{\mathrm{b}} - E)} \tag{9}$$