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Infrared detector based on modulation-doped quantum-dot structures

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We investigate a detector model, where quantum dots are surrounded by potential barriers created by modulation doping. Strong separation of the localized ground states and continuum conducting states drastically increases the photoelectron capture time. At room temperatures the photoelectron capture is conditioned by electron diffusion in the potential relief. Monte-Carlo modeling with diffusion-limited capture in the modulation-doped quantum-dot structures is used to calculate carrier lifetime and photoconductive gain as functions of the electric field. We evaluate the photodetector characteristics and show that photoconductive gain is substantially improved due to longer lifetimes of photoelectrons. Optimized quantum-dot structures have a strong potential for development IR room-temperature detectors.

1 Introduction

Quantum-dot infrared photodetectors (QDIPs) are considered as promising candidates for middle and long-wavelength infrared photodetectors [1-3]. It was expected that QDIPs would outperform quantum well infrared photodetectors (QWIPs) due to their potential advantages, first of all, longer lifetime of excited electrons, which results in higher responsivity and high-temperature operation [2, 4, 5]. Long excited-state lifetime was associated with greatly suppressed electron-phonon scattering due to quantization of electron energy levels in quantum dots [4, 5]. However, detailed experiments [6] and complex analysis [7] have shown that the electron energy relaxation in quantum dots is just a few times slower than that in quantum wells. According to advanced theoretical investigations, various strong many-body effects wash out the electron levels and render short carrier lifetime. Therefore, the electron-phonon relaxation in quantum dots cannot provide long carrier lifetime desired for high responsivity.

Nevertheless, we believe that specially-engineered quantum-dot structures can offer longer lifetimes because of the geometry of photocarrier dot-traps, restricted in all three dimensions. As well as in the high-mobility heterostructures, the capture processes could be substantially suppressed, if the dot-traps are separated from the "conducting channels" by potential barriers created by means of the modulation doping. In our previous works [8–10] we considered various realizations of potential barriers and their effects on the detector performance. In the current paper, we continue investigations of a model of the photodetector operating at the room temperature, where the electron mean free path is relatively short and the photoelectron capture is determined by the electron diffusion in the field of potential barriers surrounding the charged dots [10]. In Ref. [10], we obtained a set of analytical results related to the trapping cross-section at small electric fields applied to the structure. Here, we develop Monte-Carlo simulations to model scattering and capture processes in the electric field.

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2 Model

We consider an active area consisting of spherical quantum dots and doped interdot area. Electrons from impurities populate quantum dots and depletion regions around the dots. The total electron potential shown in Fig. 1 is given by a sum of the band-offset potential, $U(r)$, and the electrostatic potential, $V(r)$, created by electrons bounded in quantum dots and by ionized donors outside the dots ($r > a$). Note, that the number, N, of confined electrons is determined by the concentration of donors through the electroneutrality condition. For $N >> 1$, we can justify the spherically-symmetric distribution of the charge as well as the quasi-classical approximation for the electron Fermi energy. In this case, outside the dot, the electrostatic potential is

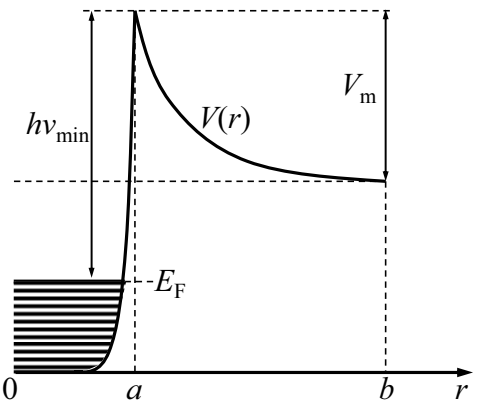

Fig. 1 Energy band diagram.

$$V(r) = V_0\left(\frac{b}{r} + \frac{r^2}{2b^2} - \frac{3}{2}\right), \qquad V_0 = \frac{eN}{\varepsilon b(1-(a/b)^3)}, \tag{1}$$

where ε is the dielectric permittivity. As seen, the electrostatic potential may be controlled over a wide range by changing the characteristic distances associated with the structure.

Considering capture processes, we take into account that at the room temperature the relaxation in a dot is very fast. Therefore, we assume that an electron is captured with probability α at $r < a$, and there is no capture outside the dot. Without an electric field, the trapping cross-section is [10]

$$\sigma = \pi\alpha a^2\tilde{v}\,\exp\left(-\frac{eV_m}{kT}\right)\left(1+\frac{3}{4}\frac{\alpha a}{\ell}F(V)\right)^{-1}, \tag{2}$$

$$F = a\,\exp\left(-\frac{eV_m}{kT}\right)\int_a^b \frac{dr}{r^2}\,\exp\left(\frac{eV(r)}{kT}\right), \tag{3}$$

where $\tilde{v}$ is the electron thermal velocity, ℓ is the electron mean free path, and $V_m = V(a)$. Note, that the suggested model is valid, if for the electron moving in the potential $V(r)$ with a thermal energy $\sim kT$ the position of the turning point is close to the dot. This condition is satisfied for $a \geq 3$ nm [10]. Finally, the electron capture time is given by $\tau_{capt} = (4\pi N_d a D)^{-1}$, where N_d is the dot concentration and D is the electron diffusion coefficient. The equations above completely describe the electron capture in the system of charged dots in the absence of the electric field. Below, we consider the same model to investigate effects of the electric field.

3 Results and discussion

The ensemble Monte-Carlo simulation method is used to investigate diffusion-limited photoelectron capture in the potential relief created by the doping of the interdot area. Specifically, we study InAs quantum dots embedded into the GaAs matrix with Si doping. Our simulation scheme takes into account electron scatterings on acoustic, polar, and intervalley phonons. The simulation includes an electron transport in Γ, L, and X valleys. At the room temperature, both elastic and inelastic electron scattering processes are determined by the electron-phonon interaction.

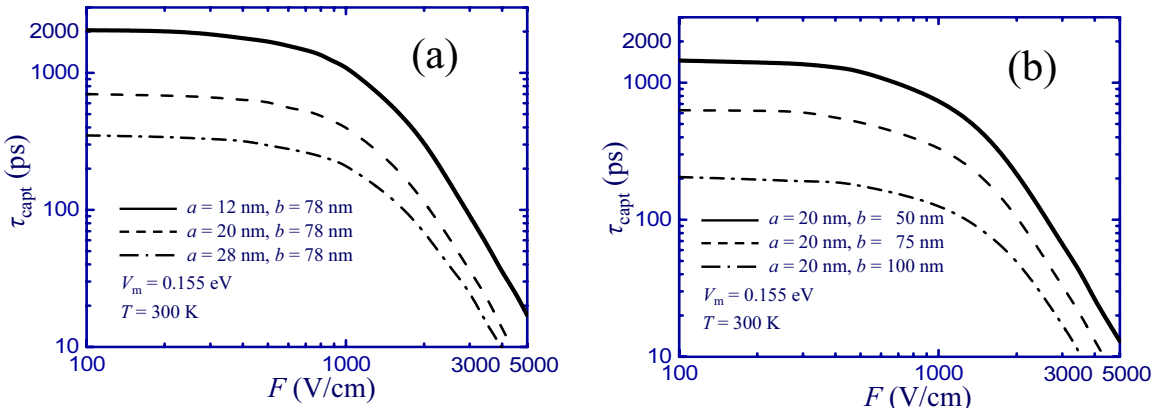

Fig. 2 Dependences of the photoelectron capture time on the electric field applied to the structure for various values of the dot radius (a) and the interdot distance (b).

We consider electric fields, which provide strongly nonequilibrium electron distributions, but, at the same time, which are small to initiate the avalanche processes or to modify significantly the barriers.

In Fig. 2, we present dependences of the photoelectron capture on the electric field applied to the structure. As seen, the capture time weakly depends on the field in the region of small fields. In this range, absolute values of the capture time are determined by a size of the dot and the dot concentration. Above the characteristic value $F_c \sim 1$ kV/cm, the capture time substantially decreases with an increase of F. Values of τ_{capt} changes by two orders of magnitude, when the electric field increases from 1 to 3 kV/cm. Note, that such behavior is practically insensitive to the structure geometry.

Figure 3 demonstrates the dependences of the capture time on a height of the potential barrier. Again, at electric fields below F_c, the electron capture time shows dependences, which are close to the exponential dependence obtained in the absence of the electric field (Eq. (2)). In the higher electric fields, the dependences τ_{capt} on the barrier potential become weaker. At $F > 5$ kV/cm, electron capture is practically independent on the barrier height for the barriers with $V_m < 0.2$ eV.

The main effects of the electric field on the processes of electron capture can be understood in terms of the electron heating. Average energies of Γ and L-electrons obtained in the electric field are shown in Fig. 4. Taking into account that Γ-electrons dominate in the photoelectron transport, we see that in the fields below ~1 kV/cm the electrons are weakly heated by the field. In the higher fields, above 2 kV/cm, the average energy is proportional to the electric field. As the electrons are heated to energies comparable with V_m, they can overcome the potential barriers with the higher the probability. Therefore, the electron capture time decreases as the electric field is increased, as it is shown in Figs. 2 and 3. Note, that the above effects can be described by Eqs. (2) and (3), if the parameter kT is replaced by $\tilde{\varepsilon}$.

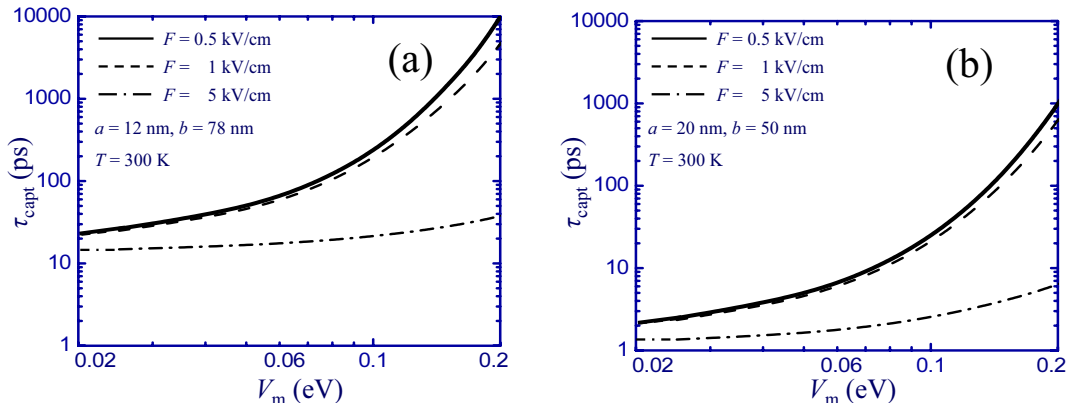

Fig. 3 Dependences of the photoelectron capture time on the potential barrier.

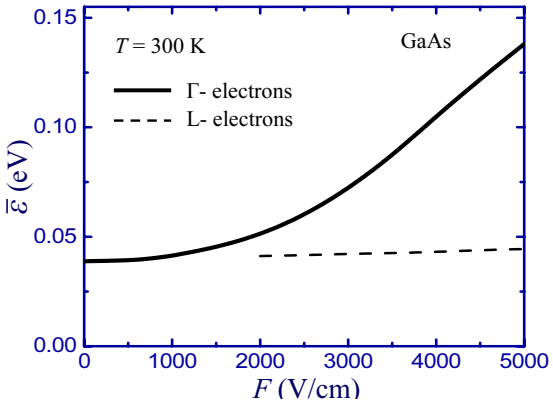

Fig. 4 Average electron energy as a function of the electric field.

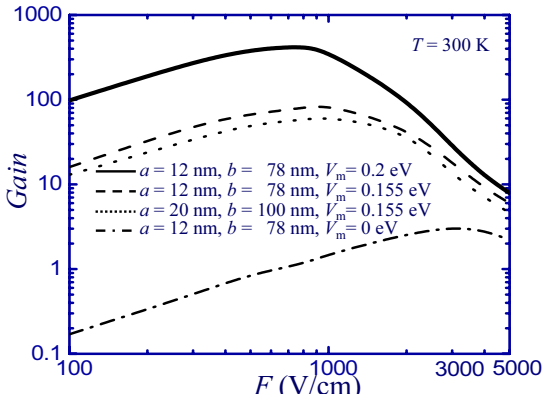

Fig. 5 Photoconductive gain as a function of the electric field.

It is also important to note that at the room temperature, the electron mean free path with respect to the inelastic electron scattering on the optical phonons is ~ 7 nm, which is smaller than the dot diameter. Therefore, the electron capture is insensitive to the relaxation processes in the dots. The elastic electron mean free path is ~ 20 nm, which is substantially smaller than the inter-dot distance. Thus, heating does not change the hierarchy of the relaxation lengths and characteristic distances and, therefore, heating is practically independent on geometry of the structure.

With the calculated electron capture time, we proceed to study the photoconductive gain as a function of the electric field. The gain is determined as,

$$g = \tau_{capt} / \tau_{tr} , \qquad (4)$$

where τ_{tr} is the transit time across the active region of the device. Taking the length of the active region of 1μm, we calculate the transit time using the Monte Carlo simulations. The dependence of the gain on the biased field is shown in Fig. 5. As seen, in the structures with potential barriers, the gain reaches a maximum value at ~1 kV/cm, which is also the characteristic field for dependences shown Figs. 2 and 3. At lower fields the gain increases due to a decrease of the transit time; at higher fields, it decreases due to substantial decrease of the capture time.

In summary, quantum dot structures with potential barriers separating the localized electron states and conducting states have a strong potential for development room-temperature IR detectors. They provide longer photoelectron lifetimes, which allow one to improve the photoconductive gain, responsivity, and noise characteristics [9,10]. Maximum value of the gain is limited by electron heating, which increases the probability of capture processes. Detailed Monte Carlo simulations show the gain can be improved by three – four orders of magnitude due to the proper engineered potential barriers.

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References

[1] Lin Jiang, Sheng S. Li, Nien-Tze Yeh et al., Appl. Phys. Lett. **82**, 1986 (2003).
[2] W. Zhang, H. Lim, M. Taguchi et al., Appl. Phys. Lett. **86**, 191103 (2005).
[3] P. Bhattacharya, X. H. Su, S. Chakrabarti et al., Appl. Phys. Lett. **86**, 191106 (2005).
[4] V. Ryzhii, Semicond. Sci. Technol. **11**, 759 (1996).
[5] J. Phillips, J. Appl. Phys. **91**, 4590 (2002).
[6] Y. Toda, O. Moriwaki, M. Nishioka, and Y. Arakava, Phys. Rev. B **82**, 4114 (1999).
[7] R. Fereira and G. Bastard, Appl. Phys. Lett. **74**, 2818 (1999).
[8] V.V. Mitin, V.I. Pipa, A.V. Sergeev et al., Infrared Phys. and Technol. **42**, 467 (2001).
[9] V. Ryzhii, I. Khmyrova, V. Mitin et al., Appl. Phys. Lett. **78**, 3523 (2001).
[10] A. Sergeev, V. Mitin, and M. Stroscio, Physica B **316/317**, 369 (2002).

