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Quantum-dot photodetector operating at room temperatures: diffusion-limited capture

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Abstract

Recent investigations have shown very promising characteristics of quantum-dot far-infrared photodetectors at 150–300 K. We propose a device model for the quantum-dot photodetector operating at high temperatures, where the electron mean free path due to electron–phonon scattering is small. In this temperature range, the electron energy relaxation in a quantum dot is very fast, so that the photoelectron capture is determined by electron diffusion in the field of potential barriers surrounding the charged quantum dots. The model with diffusion-limited capture is used to evaluate the photodetector performance.

Keywords: Quantum-dot photodetector; Electron capture

Many applications, such as flight control, night vision, and early warning systems, require sensitive far-infrared microsensors to employ in high-density focal plane arrays. Low cost and high operating temperature would significantly increase commercial market of infrared detectors. Quantum-well infrared photodetectors have been successfully employed in imaging devices operating at liquid nitrogen temperatures and below [1]. The quantum-well detectors demonstrate the detectivity of $\sim 10^{10}\,\mathrm{cm\,Hz^{1/2}/W}$ for $\lambda = 10\,\mu\mathrm{m}$ at 77 K. With decrease in the operating temperature to 35 K, the detectivity rises to $\sim 10^{13}\,\mathrm{cm\,Hz^{1/2}/W}$. High-temperature limitations of quantum-well structures are mainly conditioned by the tremendous decrease of sensitivity, caused by significant reduction of photocarrier lifetime above nitrogen temperatures [1].

The quantum dot arrays were thought to provide longer lifetimes of photoelectrons due to the phonon bottleneck effect in quantum dots [2–4]. However, experiments [5] and detailed theory [6] have demonstrated the absence of the phonon bottleneck with the electron energy relaxation in the quantum dot being just a few times slower than the relaxation in a quantum well. Recently experimentalists paid special attention to the modulation-doped AlGaAs/GaAs structures with InAs quantum dots [7,8]. In these structures, a long lifetime of photoexcited carriers was achieved by means of potential barriers that prevented photoelectron capture into quantum dots. The long lifetime and high mobility result in significant photosensitivity, which survives up to

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190 K [7]. Very recent experiments with quantum dots embedded in the channel region of modulation-doped structures demonstrate excellent performance of these photodetectors [8]. The record detectivity of $5\times10^{10}\,\mathrm{cm\,Hz^{1/2}/W}$ has been observed at 80 K. Moreover, the detectivity of $6\times10^{8}\,\mathrm{cm\,Hz^{1/2}/W}$ has been reached at room temperatures.

Experimental results of Refs. [7,8] convincingly show that quantum-dot detectors may outperform quantum-well structures in photosensitivity because of the geometry of photocarrier dot traps, restricted in all the three dimensions. At high temperatures, the electron mobility is limited by electron–phonon scattering, and electron relaxation of captured electrons is very fast. Therefore, the photoelectron lifetime is determined by the electron diffusion.

We consider the following model of the electron capture into the spherical quantum dot. Let us assume that there is the critical radius, $r=a$, where an electron is captured with probability α. There is no capture if $r>a$. In the frame of this model, the trapping cross section may be presented as

$$\sigma=\pi\alpha a^2\tilde{v}\exp\left(-eV(a)/kT\right)\times\left[1+\frac{3}{4}\frac{\alpha a}{l}F(V)^{-1}\right],\qquad(1)$$

where $\tilde{v}$ is the electron thermal velocity and l is the electron mean free path. The diffusion coefficient is given as $D=l\tilde{v}/3=\mu kT/e$, where μ is the electron mobility. The function $F(V)$ is determined by the potential $V(r)$, created by electrons inside the dot and ionized donors outside the dot:

$$F=a\exp\left(-\frac{eV(a)}{kT}\right)\int_a^b\frac{\mathrm{d}r}{r^2}\exp\left(\frac{eV(r)}{kT}\right),\qquad(2)$$

where we assume that the potential is negligible if $r>b$. Note that Eqs. (1) and (2) are analogous to the Pekar formula [9], which was widely used to describe electron trapping by attractive centers.

In atomic systems, the trapping by the repulsive potential is well described by the Bonch–Bruevich model based on electron tunneling through potential barriers [10]. In the quasiclassical approximation, the position of the turning point is given by

$$R_t\simeq a_0\left(\frac{Ry}{kT}\right)^{2/3}\left(\frac{Zm_0}{m}\right)^{1/3},\qquad(3)$$

where a_0 is the Bohr radius, Ry is the Rydberg constant, Z is the charge of the trapping center, m is the electron mass, and m_0 is the free electron mass. At room temperatures, $R_t\simeq3.5$ nm. If the radius of a quantum dot is larger than R_t, one can use Eqs. (1) and (2), associating the critical radius, a, with the radius of the quantum dot. The electron capture is conditioned by the electron diffusion in the interdot space.

If $V=0$ (no electrons in the dot), the trapping cross section obtained from Eqs. (1) and (2) is

$$\sigma=\pi\alpha a^2\tilde{v}\left[1+\frac{3}{4}\frac{\alpha a}{l}\right]^{-1}.\qquad(4)$$

Keeping in mind that the electron lifetime is $\tau_l=(N\sigma)^{-1}$ (N is the dot concentration), at high temperatures, where $l=l_{e-ph}\ll a$, we find

$$\tau_l=(4\pi NaD)^{-1}.\qquad(5)$$

Now we consider diffusion-limited electron trapping in the structure with quantum dots surrounded by repulsive potential barriers, which are created by interdot doping [11]. Electrons tripped from impurities populate quantum dots and create depletion areas around them. The potential relief (Fig. 1) is produced by electrons bounded in quantum dots and by ionized donors placed outside the dots. Such relief may be obtained by doping of GaAs by Si. If the average

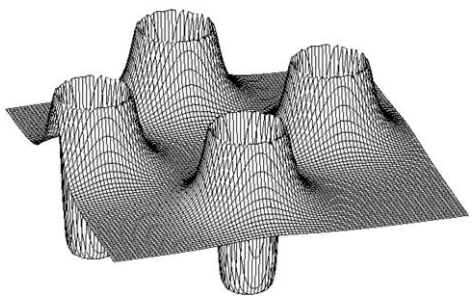

Fig. 1. Potential relief of quantum dot array.

number of electrons per dot is large, $N \geqslant 10$, the positive charge of donors is uniformly distributed in a spherical shell $a \leqslant r \leqslant b$, where $2b$ is the interdot distance. Outside the dot, the electron potential energy is

$$V = V_0\left(\frac{1}{\xi} + \frac{\xi^2}{2} - \frac{3}{2}\right), \tag{6}$$

$$V_0 = \frac{Ne^2}{\varepsilon b(1-(a/b)^3)}, \tag{7}$$

for $a \leqslant r \leqslant b$ and $V = 0$ for $r > b$. Here, ε is the static dielectric permittivity and $\xi = r/b$. In the structure with potential barriers, bound-to-continuum phototransitions are possible if

$$h\nu \geqslant U_0 - E_F + V(a), \tag{8}$$

where E_F is the Fermi energy of electrons in the dot, and U_0 is the band-offset. For example (see Ref. [11]), for quantum dots made of $In_xGa_{1-x}As$ in an $Al_yGa_{1-y}As$ matrix, with $x = 0.95$ and $y = 0.22$, the band-offset, U_0, is 220 meV. Using material parameters $m = 0.067m_0$, $\varepsilon = 12$, for $N_d = 10^{16}\,cm^{-3}$, $N = 20$ and $a = 12\,nm$, we find that $E_F \approx 100\,meV$, $V_m = 0.155\,meV$, and $b = 78\,nm$.

If $eV(a) \ll kT$, the trapping cross section is the same as in the flat-band structure (Eqs. (4) and (5)). If $eV(a) \geqslant kT$, the cross section is

$$\sigma = \frac{\pi\alpha a^2\tilde{v}}{1+\frac{3}{4}(\alpha a/l)(kT/eV(a))}\exp\left(\frac{-eV(a)}{kT}\right). \tag{9}$$

Exponential dependence of the cross section on the barrier potential allows one to increase significantly the electron lifetime. With the factor $kT/eV(a) \sim 0.2$, the second term in the denominator is small, and the electron lifetime is given by

$$\tau_l = (\pi N a^2\tilde{v})^{-1}\exp\left(\frac{eV(a)}{kT}\right). \tag{10}$$

Considering characteristics of the photodetector, we start with the photoconductive gain, which is defined as

$$g = \tau_l/\tau_{tr}, \tag{11}$$

where $\tau_{tr} = L/v_d$ is the transit time, L is the distance between electrodes, and v_d is the drift velocity. According to Eqs. (5) and (11), in the case of the flat-band structure, the gain is independent of the electron mean free path. In the structure with potential barriers, the electron lifetime increases by the factor of $(a/l)\exp(V(a)/kT)$ in comparison with that in the flat-band structure. According to Eq. (11), the potoconductive gain also increases by the same factor. The responsivity of the detector is directly proportional to the photoconductive gain. Therefore, we expect high responsivity for the quantum-dot structure with potential barriers.

The basic noise characteristic of the detector is the noise equivalent power (NEP), which is defined as the noise power normalized by the square root of the frequency band. The intrinsic noise in the quantum-dot detector is the generation–recombination (G−R) noise associated with random thermal excitations and decay of carriers. The NEP conditioned by G–R noise is given by

$$NEP_{G-R} = 2h\nu\sqrt{\frac{n_{th}}{\tau_l}}, \tag{12}$$

where n_{th} is the number of the thermally excited carriers.

The presence of the exponential factor in the electron lifetime (Eq. (10)) does not directly improve NEP, because the increase in the photocarrier lifetime is compensated by the increase in the number of thermoexcited carriers at low-energy levels [the levels with energy $\sim(h\nu - V_m)$ with respect to the Fermi level]. Thus, at high temperatures, the NEP for the structure with potential barriers is a/l times better than that for the flat-band structure. Also, the high gain allows one to reduce the detector volume and to sacrifice the high responsivity in favor of the noise equivalent power.

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References

[1] B.F. Levine, J. Appl. Phys. 74 (1993) R1.
[2] U. Bockelmann, G. Bastard, Phys. Rev. B 42 (1990) 8947.
[3] V. Ryzhii, Semicond. Sci. Technol. 11 (1996) 759.
[4] H.C. Liu, Physica E 170–173 (2000) 170.
[5] Y. Toda, O. Moriwaki, M. Nishioka, Y. Arakava, Phys. Rev. B 82 (1999) 4114.

[6] R. Fereira, G. Bastard, Appl. Phys. Lett. 74 (1999) 2818.
[7] S.-W. Lee, K. Hirakawa, Y. Shimada, Appl. Phys. Lett. 75 (1999) 1428.
[8] J.W. Kim, J.E. Oh, S.C. Hong, C.H. Park, T.K. Yoo, IEEE Electron Device Lett. 21 (2000) 329.
[9] S.I. Pekar, Zh. Eksp. Teor. Fix. 20 (1950) 267.
[10] V.L. Bonch-Bruevich, Sov. Phys. Solid State 6 (1964) 1615.
[11] V.V. Mitin, V.I. Pipa, A.V. Sergeev, M. Dutta, M. Stroscio, Infrared Phys. Technol. 42 (2001) 467.