Enhanced Signal-to-Noise in Photodetectors due to Interface Phonon-assisted Transitions

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INTRODUCTION

This paper addresses novel photodetectors with dramatic enhancement in detectivity, based on rapid interface phonon-assisted transitions combined with quantum engineering of phonon and electron states in nanostructures. Based on the concepts we introduced previously [1-2] for heterosturcture lasers, which have resulted in extremely large enhancements in the optical gain of quantum-well-based lasers, this work examines dramatic enhancement of photodetectivity in novel quantum-well based photodetectors in the first known embodiment that facilitates the detection of photons over a wide range of frequencies. Herein, we consider a triple quantum-well structure with one single well and one double well; the relationship between the energy levels should be: $E_3=E_2$'; $E_3-E_1=E_4'-E_2=E_{photon}$; $E_2'-E_2=E_{phonon}$, as in Fig. 1.
This energy-level structure facilitates the absorption of a photon, emission of a phonon, and the absorption of a photon with the same wavelength as the original photon. E_1 is the first energy level of the single well, and E_3 is the second energy level of it. In addition, E_2, E_2', E_4, and E_4' represent the first, second, third, and forth energy levels for the double quantum well.
With reference to Fig. 1, it is straightforward to see that there will be a dramatic signal-to-noise enhancement in the current, $I_{sn,E1}$, from the deepest state E_1, relative to $I_{sn,E2}$, from the deepest state E_2 (without phonon-assisted transition and second photon absorption), as given by the Richardson formula:

$$\frac{I_{sn,E1}}{I_{sn,E2}}=\frac{e^{-\frac{2E_{photon}-E_{phonon}}{kT}}}{e^{-\frac{E_{photon}}{kT}}}=e^{-\frac{E_{photon}-E_{phonon}}{kT}} \qquad (1)$$

In this equation, $E_{photon}=E_3-E_1=E_4-E_2$ and $E_{phonon}=E_2^{'}-E_2$.

For example if $\frac{E_{photon}-E_{phonon}}{kT}=8$, a dramatic 1/3,000 reduction can be realized.

THEORY

Considering the transfer efficiency, from the Fermi Golden Rule [4],

$$\frac{1}{\tau_i}=\frac{2\pi}{\hbar}\sum_f\left|\left\langle f\left|\tilde{H}\right|i\right\rangle\right|^2\delta(E_f-E_i) \qquad (2)$$

From Fig. 2., it is evident that E_1 E_2 E_4 are even, but E_3 E_2' E_4' are odd. As mentioned previously, E_1 to E_3, and E_2 to E_4' as the photon absorbing levels; the splitting of E_2' to E_2 as phonon emitting levels. The phonon-assisted transition has characteristic rates of about one ps or less [4].
For calculating the energy levels in the quantum wells, we use the Schrödinger equation with effective mass mismatch at heterojunctions [1].

$$\begin{cases}-\frac{\hbar^2}{2m_b^*}\frac{\partial^2}{\partial z^2}\Psi(z)+V\Psi(z)=E\Psi(z) & z\le -l_w/2\\ -\frac{\hbar^2}{2m_w^*}\frac{\partial^2}{\partial z^2}\Psi(z)=E\Psi(z) & -l_w/2\le z<l_w/2\\ \frac{\hbar^2}{2m_b^*}\frac{\partial^2}{\partial z^2}\Psi(z)+V\Psi(z)=E\Psi(z) & l_w/2\le z\end{cases} \qquad (3)$$

The interface phonon modes of our structure produce a rapid phonon-assisted transfer of electrons [1,2.4] when $E_2'-E_2=E_{phonon}$ in our structure.
For the photodetector modeled here, there are five interfaces. In order to calculate the potential in our system, we then write the potentials of the seven regions as the following:

$$\begin{cases}\Phi=Ae^{qz} & z<0\\ \Phi=Be^{qz}+Ce^{-qz} & 0\le z\le d_1\\ \Phi=De^{q(z-d_1)}+Ee^{-q(z-d_1)} & d_1\le z\le d_2\\ \Phi=Fe^{q(z-d_2)}+Ge^{-q(z-d_2)} & d_2\le z\le d_3\\ \Phi=He^{q(z-d_3)}+Ie^{-q(z-d_3)} & d_3\le z\le d_4\\ \Phi=Je^{q(z-d_4)}+Ke^{-q(z-d_4)} & d_4\le z\le d_5\\ \Phi=e^{-q(z-d_5)} & z>d_5\end{cases} \qquad (4)$$

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Where A, B, C, D, E, F, G, H, I, J and K are constants.

At the heterointerfaces of the six regions, the following two conditions have to be satisfied [2]:

$$\Phi_1(Z) = \Phi_2(Z) \qquad (5)$$

$$\varepsilon_1 \frac{\partial \varepsilon_1}{\partial z} = \varepsilon_2 \frac{\partial \varepsilon_2}{\partial z} \qquad (6)$$

Then we can get the secular equation of our system,

$$\frac{Je^{q(d_5-d_4)} + Ke^{-q(d_5-d_4)}}{Je^{q(d_5-d_4)} - Ke^{-q(d_5-d_4)}} = -\frac{\varepsilon_3}{\varepsilon_1} \qquad (7)$$

where ε_1 is the dielectric function of the substrate, ε_3 is the dielectric function of the double quantum well.

Solving this equation yields the interface phonon modes of our system.

As long as we have the interface phonon modes, we can then calculate the potential by using the following normalization condition:

$$\frac{\hbar}{2\omega L^2} = \sum \frac{1}{4\pi} \frac{1}{2\omega} \frac{\partial \varepsilon_i(\omega)}{\partial \omega} \int_{R_i} dz (q^2 |\Phi_i(q,z)|^2 + \left| \frac{\partial \Phi_i(q,z)}{\partial z} \right|^2) \quad (8)$$

Substituting the potentials into this condition, it becomes:

Here we substitute the relationship between these constants we obtained from the previous boundary conditions into this condition we can get a equation (9) which has just one unknown A. The Frohlich potential for the phonon-assisted transitions follows straightforwardly.

RESULTS AND DISCUSSION

In conclusion, we have explored a novel approach

$$\frac{\partial \varepsilon_1(\omega)}{\partial \omega} qA^2 + \frac{\partial \varepsilon_2(\omega)}{\partial \omega} q(B^2(e^{2qd_1} - 1) + C^2(1 - e^{-2qd})) +$$
$$\frac{\partial \varepsilon_1(\omega)}{\partial \omega} q(D^2(e^{2q(d_2-d_1)} - 1) + E^2(1 - e^{-2q(d_2-d_1)}))$$
$$+ \frac{\partial \varepsilon_3(\omega)}{\partial \omega} q(F^2(e^{2q(d_3-d_2)} - 1) + G^2(1 - e^{-2q(d_3-d_2)}))$$
$$+ \frac{\partial \varepsilon_1(\omega)}{\partial \omega} q(H^2(e^{2q(d_4-d_3)} - 1) + I^2(1 - e^{-2q(d_4-d_3)}))$$
$$+ \frac{\partial \varepsilon_3(\omega)}{\partial \omega} q(J^2(e^{2q(d_5-d_4)} - 1) + K^2(1 - e^{-2q(d_5-d_4)})) - \frac{\partial \varepsilon_1(\omega)}{\partial \omega} q = \frac{4\pi\hbar}{L^2}$$

for using phonon-assisted transitions to enhance the signal-to-noise in photodetectors by several orders of magnitude. Using this model, we have identified several different structures suitable as photodetectors incorporating phonon-assisted transitions: one based on GaAlAs/GaAs material system, one based on InGaAs/InAs material system and the other one base on InAlAs/InP material system.

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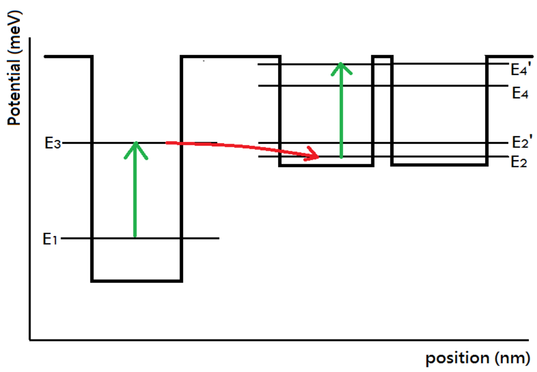

Fig. 1. Structure of photodetector.

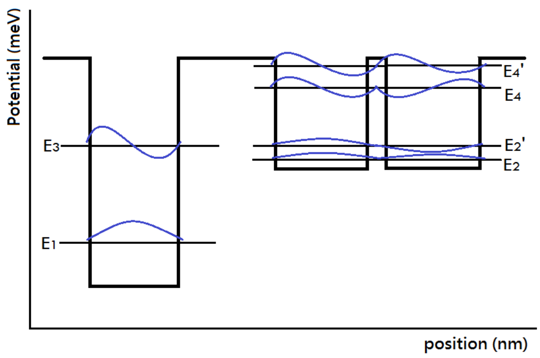

Fig. 2 Wavefunctons of photodetector.