Photocurrent induced by intersubband transition in a type II and broken-gap quantum well system

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We demonstrate theoretically that when an InAs/GaSb based type II and broken-gap quantum well is subjected to a light field, conductance can be observed along the growth direction due to charge transfer between electron and hole layers. A sharp peak can be observed in conductance within sub-THz bandwidth. The peak shifts to the lower frequency (red-shift) with increasing temperature. Our results indicate that InAs/GaSb based quantum well systems are of potential to be applied as sub-THz photovoltaic devices.

1 Introduction

InAs/GaSb based type II and broken-gap quantum well (QW) structure has a unique electronic subband structure that the valance subbands in GaSb layer can be higher than the conduction subband in InAs layer and that holes and electrons are separated spatially in the GaSb and InAs layers respectively. In recent years, this unique QW structure has been applied as advanced optical devices such as uncooled infrared detectors [1], negative persistent photoconductors [2, 3], etc. Very recently, it is also realized that InAs/GaSb based electron-hole bilayer systems can also be used as photodetectors [4] and photovoltaic detectors [5]. This has shed some lights on employing such systems as novel photovoltaic devices. In this work, we explore theoretically the possibility to apply InAs/GaSb based type II and broken-gap QW systems as photocurrent devices working at terahertz (10^{12} Hz or THz) or sub-THz bandwidth which lies between electronic and optical phenomenon. This proposal is mainly based on the fact that in such systems, the electrons and holes can be excited by the linearly polarized light fields into different layers due to the overlap of electron and hole wavefunctions. This can lead to a situation where the charge numbers in different layers are modified by the applied light fields and a current circuit can therefore be achieved. Thus, the photocurrent can be induced along the growth direction.

2 Outline of the theoretical approach and results

In this work, we consider a type II QW structure in which a two-dimensional electron gas (2DEG) and a 2D hole gas (2DHG) are separated spatially in two layers. When an electromagnetic (EM) field which is polarized linearly along the growth direction of the QW is applied to the system, we can employ the semi-classic Boltzmann equation as the governing transport equation to study the consequence of the presence of the EM field. For the first moment, the mass-balance equation [6] can be derived by multiplying ∑_k to both sides of the Boltzmann equation. In doing so and assuming that the electron and hole distributions can be described by the statistical energy distribution functions, we can obtain a rate-equation. On the basis of this rate equation, after considering:

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(i) under the action of an EM driving field \( V(t) = V_0 e^{i\omega t} \) with \( \omega \) being the frequency of the EM field, the electron number in the QW is the difference between the mobil electron number and the emitted electron number; (ii) for case of a weak EM field so that a linear response is achieved, i.e., \( I(t) = I_0 e^{i\omega t} \) with \( I(t) \) being the current in the circuit; and (iii) the electronic transition rate is induced by electron or hole interactions with the radiation field, which is given by the Fermi’s golden rule, the conductance in the current circuit is obtained as

\[
G = \text{Re}(I_0/V_0) = \frac{\kappa \omega^2 \lambda_E}{(\lambda_E + \lambda_C)^2 + \omega^2} \quad \text{with} \quad \kappa = \frac{e^3 m_e^* S}{\pi \hbar^2} f_e(\epsilon_e),
\]

where \( S \) is the area of the 2D-plane, \( m_e^* (j = e \text{ or } h) \) is the electron or hole effective mass, \( f_e(x) = [e^{(x-E_F)/k_BT} + 1]^{-1} \) and \( f_h(x) = [e^{(E_F-x)/k_BT} + 1]^{-1} \) with \( E_F \) being the Fermi energy,

\[
\lambda_E = C \frac{m_e^* |X_{eh}|^2}{m_e^* n_e} f_e(x_h^+)[1 - f_h(x_e^-)] \quad \text{and} \quad \lambda_C = C \frac{m_e^* |X_{eh}|^2}{m_h^* n_h} f_h(x_e^+)[1 - f_e(x_h^-)]
\]

are respectively the electron emission and capture rates, \( C = 4(eF_0)^2/|\hbar \omega^2 (m_e^* + m_h^*)|, F_0 \) and \( \omega \) are respectively the electric field strength and frequency of the EM field, \( x_i^+ = (m_e^* \epsilon_e + m_e^* \epsilon_e \pm m_e^* \hbar \omega)/(m_e^* + m_h^*) \), and \( X_{ij} = \int dx \psi_i^*(x) d\psi_j(x)/dz \). Moreover, \( \psi_i(z) \) and \( \epsilon_i \) are respectively the ground-state wavefunction and subband energy for an electron or a hole, and \( n_i \) is the density for a 2DEG or a 2DHG. Here we have considered that only the highest hole subband and the lowest electron subband are occupied by holes and electrons.

### 3 Results and discussion

Here we consider a typical InAs/GaSb QW in which the broken-gap structure can be achieved. The widths of the InAs and GaSb layers are taken respectively as \( L_{\text{InAs}} = 17 \text{ nm} \) and \( L_{\text{GaSb}} = 5 \text{ nm} \). The electron and hole wavefunctions and subband energies along with the electron and hole densities are obtained by solving self-consistently the Schrödinger equation and Poisson equation. The results obtained from this calculation are: \( n_e = 1.14 \times 10^{12} \text{ cm}^{-2} \), \( n_h = 3.10 \times 10^{11} \text{ cm}^{-2} \), \( \epsilon_e = 32.0 \text{ meV} \), \( \epsilon_h = 106.3 \text{ meV} \) and \( E_F = 104.0 \text{ meV} \). Here the energy is measured from the bottom of the conduction band in the InAs layer. The charge distribution in such a QW is shown in Fig. 1, from which one can find that although the hole density \( n_h \) is lower than the electron density \( n_e \), the hole distribution is more localized than electron distribution. Therefore, the overlap between the electron and hole distribution is mainly through the penetration of electron wavefunction into the GaSb layer.

In Fig. 2, the conductance in the current circuit is shown as a function of the radiation frequency at a fixed radiation intensity for different temperatures. A sharp peak of the conductance can be observed at sub-THz regime \( \omega \sim 0.1 \text{ THz} \). This implies that a strong photocurrent can be generated from the device by sub-THz radiation fields. With increasing temperature, the conductance peak is red-shifted and lowered. This suggests that this kind of photocurrent effect can be detected at relatively low-temperatures.

In a type II and broken-gap QW structure, because both electron and hole states are occupied respectively by electrons and holes, the new channels for optical transition open up. The electron and hole interactions with a light field via absorption scattering can be achieved through the following ways. At small (large) \( k \) case, electrons (holes) in the InAs (GaSb) layer can be scattered into occupied and unoccupied state in the GaSb (InAs) layer by absorbing a photon. As a result, although the overlap of the electron and hole wavefunctions at the interface is relatively weak, a strong photocurrent can be generated.

In this work, we have demonstrated that when a linearly polarized sub-THz light field is applied to a InAs/GaSb based type II and broken-gap QW, a current circuit can be formed and photocurrent can be generated. Thus, such a structure can be used as sub-THz photovoltaic device. We hope this interesting and important theoretical finding can be verified experimentally.

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Fig. 1 Electron (solid curve) and hole (dotted curve) distribution in an InAs/GaSb quantum well. The results are obtained self-consistently for $L_{\text{InAs}} = 17$ nm and $L_{\text{GaSb}} = 5$ nm.

Fig. 2 Conductance in the current circuit as a function of radiation frequency $\omega$ at a fixed radiation intensity $F_0$ for different temperatures $T$. $L_{\text{InAs}}$ and $L_{\text{GaSb}}$ are respectively the widths for the InAs and GaSb layers and $G_0 = e^2/\hbar$.

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