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Hot Electron Effects in Infrared Multiple-Quantum-Well Phototransistor

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This paper presents a theoretical analysis of physical mechanisms responsible for operation and performance, in particular, optical gain, of infrared multiple-quantum-well (MQW) photodetectors. The influence of the device structure on the distribution of potential, which, in turn, determines the carrier injection and transport properties, is discussed. We used Monte Carlo method to study the hot electron effects in MQW phototransistor proposed earlier by the authors. It is shown that the nature of the hot electron transport in the base of MQW phototransistor plays a crucial role in determining device characteristics.

1. Introduction

In recent years multiple-quantum-well (MQW) structures have attracted considerable interest for detection of infrared radiation utilizing intraband optical transitions.[1,2] A number of different device structures of quantum-well infrared photodetectors (QWIP) have been proposed and investigated both experimentally and theoretically. In spite of the apparent simplicity, the physics of operation of MQW photodetectors, in particular, the origin of the photocurrent gain, is still not clear . Therefore more deep physical understanding is required for proper design and optimization of the QWIP device structures.

The aim of the present work is to analyze the physical effects responsible for operation of MQW photodetectors. We also present the results of numerical simulation of physical processes in one of the variants of the MQW photodetectors, called MQW infrared phototransistor, which has been proposed recently[3] by the authors.

2. Physical Effects in QWIP

Typical device structures of MQW infrared photodetectors, shown in Fig. 1, comprise narrow-gap doped multiple quantum wells, separated by wide-gap undoped barriers. MQW region is isolated by wide-gap barriers from the emitter and collector heavily doped layers, which plays the role of the contacts.

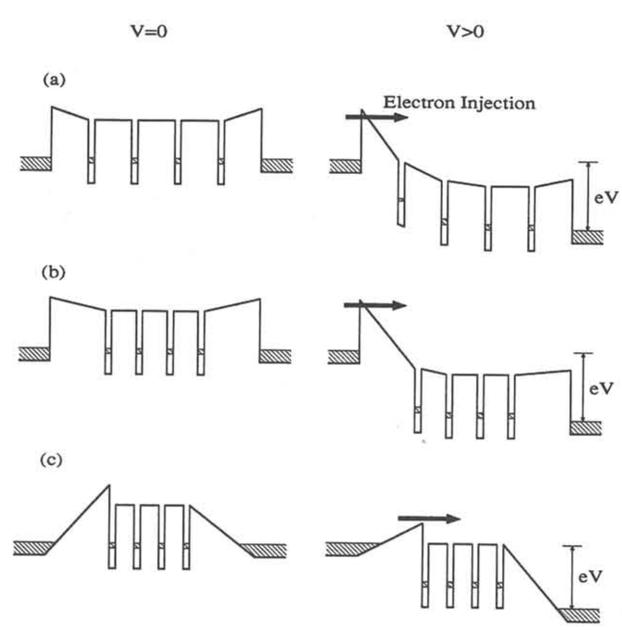

Figure 1: Schematic band diagram of MQW photodetectors: (a) identical wide rectangular barriers, (b) wide rectangular emitter and collector barriers (thermionically assisted tunnel injection), and (c) wide triangular emitter and collector barriers (thermionic injection).

The absorption of infrared radiation gives rise to an excitation of electrons from the bound state in the quantum well into the continuum states. These photoexcited electrons are collected by the collector, when a bias is applied across the structure. The resulting depletion of the MQW region of the electrons is responsible for the redistribution of potential in the MQW structure and an enhancement of the electron injection from the emitter (Fig. 2). The total photocurrent comprises the contributions of those photoexcited electrons and additionally injected electrons, which avoid capture into the quantum wells. The current of the photoexcited carriers can form only a minor fraction of the total photocurrent, which is the reason for large values of photocurrent gain.

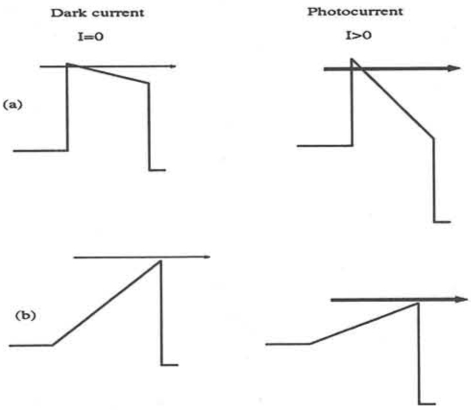

Figure 2: Schematic representation of enhancement of electron injection from emitter under illumination.

The operation of the MQW photodetectors involves a number of physical effects, of which, in our opinion, the following are very important:

- *Distribution of potential in the active region.*
- *Electron injection through the emitter barrier*, which is influenced by the distribution of potential through the change of the height and/or tunneling transparency of emitter barrier (Fig. 2).
- *Influence of potential distribution on the thermo- and photoexcitation of bounded electrons.*
- *Transport of excited and injected electrons in the MQW region*, which is determined by the potential distribution.
- *Influence of electron transport properties on the balance between bounded and continuum states electrons* trough:
  1. Dependence of capture rate into the QWs on energy distribution and valleys' population of continuum states electrons
  2. Impact ionization of bounded electrons
  3. Enhancement of thermal excitation due to heating by continuum states electrons

Thus, the distribution of the potential influences essentially the number of physical effects in QWIP. In turn, these effects govern the filling of QWs and charge distribution in the structure of QWIP, determining in such a way the potential distribution. The type of potential distribution is also strongly dependent on applied bias and structure of the QWIP, and it does not have to be uniform, as implicitly assumed in a literature.[1] It should be noted, that the extreme, emitter and collector, barriers can play a very important role, since applied bias can drops predominantly on these barriers.[3] In the next section we present the results of simulation of hot electron effects in one of the variants of QWIP.[3]

3. Modeling of Hot Electron Effects in MQW Phototransistor

Conduction band structure of MQW phototransistor[3] under biasing voltage is shown in Fig. 3. The wide

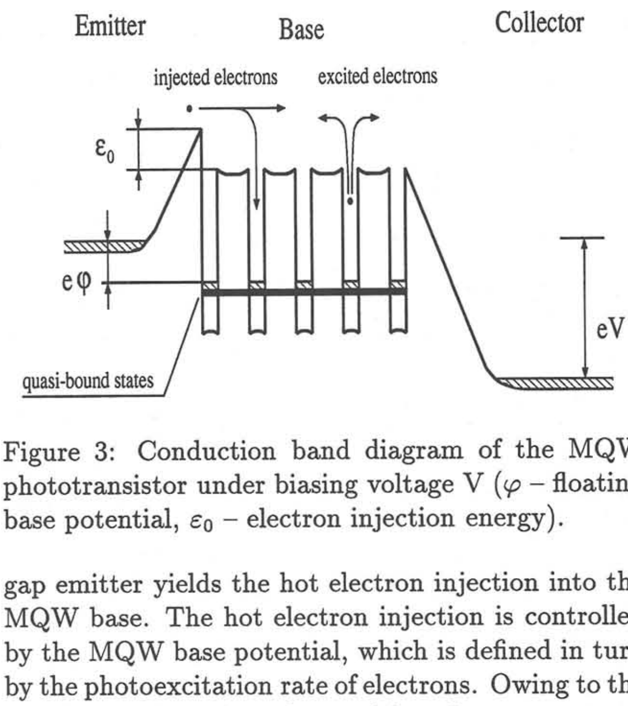

Figure 3: Conduction band diagram of the MQW phototransistor under biasing voltage V (φ – floating base potential, ε_0 – electron injection energy).

gap emitter yields the hot electron injection into the MQW base. The hot electron injection is controlled by the MQW base potential, which is defined in turn by the photoexcitation rate of electrons. Owing to the hot electron injection, the resulting photocurrent can significantly exceed the current of photoexcited electrons that leads to giant photocurrent gain. Optical gain g and responsivity R of the MQW phototransistor have the following dependence on device parameters [3]: $g = \eta_+/(1-\beta)$, $R \sim W_b \cdot g$, where W_b is the MQW base thickness, η_+ is the probability of excited electron escape from the base into the collector, and β is the base transfer factor. We simulated electron transport in the MQW base using Monte Carlo method to find the carrier energy distribution function, $F(\varepsilon, x)$, which allows the calculation of transfer factor as $\beta = 1 - \int_0^{W_b} dx \int_0^\infty d\varepsilon F(\varepsilon, x)/\tau_c(\varepsilon)/(j(0)/e)$, where $j(0)$ is electron current density at the emitter-base interface, $\tau_c = \tau_c(\varepsilon)$ is the carrier capture time. We used two models of capture time: (a) $\tau_c(\varepsilon) = \tau_0$ and (b) $\tau_c^{-1}(\varepsilon) = \tau_0^{-1} \cdot \Theta(E_{opt} - \varepsilon)$, where ε is electron energy, Θ is the step function, E_{opt} is the optical phonon energy and $\tau_0 = 4 \cdot 10^{-11} s$ is constant derived from the experimental papers. MQW phototransistors with 6 nm GaAs wells and 6 nm $Al_{0.25}Ga_{0.75}As$ barriers in the MQW base doped at $N_B = 10^{18}$ cm^{-3} were investigated at T=10 K.

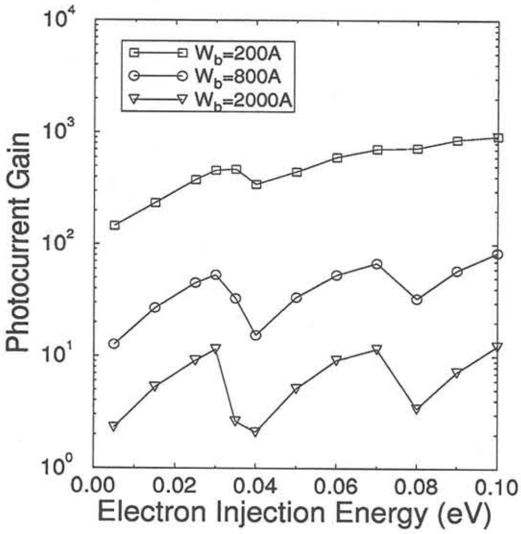

Figure 4: Optical gain as a function of electron injection energy with base thickness as a parameter.

Fig. 4 shows the calculated optical gain as a function of electron injection energy. For small base thicknesses, electron transport is close to near ballistic. Probability of electron capture into the QWs is very low due to small transit time, which leads to a giant photocurrent gain, approaching values of 10^3. Optical gain is almost monotonically increased with injection energy because of the reduction of base transit time. For larger base thicknesses, transfer factor (and optical gain) is lowered due to electron scattering in the base, which reduces average electron velocity. Moreover, optical gain becomes an oscillating function of energy, which is associated with emission of optical phonons. Thus, it is possible to enhance the photocurrent gain by proper optimization of base thickness and composition of the emitter barrier.

Normalized responsivity of MQW phototransistor calculated using different models of capture time is shown in Fig. 5. The general dependence of the responsivity on the injection energy follows that of the photocurrent gain. The model with energy-dependent capture time predicts much higher values of responsivity for small base thicknesses and high injection energies, which is due to highly nonequilibrium carrier distribution and reduced capture into the QWs. However, for more thick bases energy relaxation of hot electrons gives rise to that both models predict almost the same result.

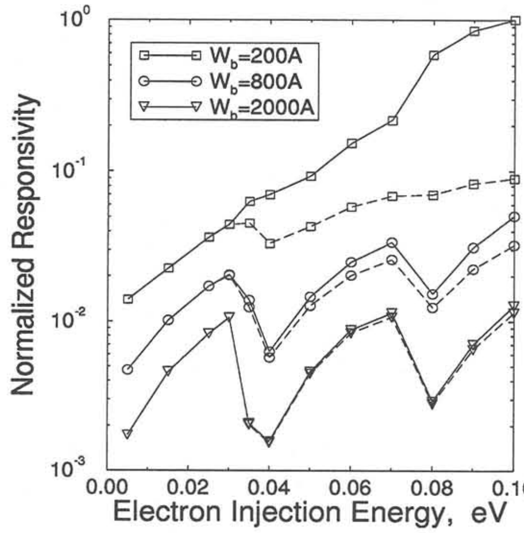

Figure 5: Normalized responsivity calculated with energy-dependent (solid line) and constant (dashed line) carrier capture times.

4. Conclusion

We have analyzed the physical effects influencing the performance of infrared QWIPs. The photocurrent gain exhibited by QWIP is closely related to the redistribution of potential, which, in turn, is interdependent with carrier injection and transport properties. We have studied using numerical simulation the hot electron effects in MQW phototransistor with triangular emitter and collector barriers and equipotential base. It is shown that optical gain of the device is defined by the properties of the hot electron transport in the base.

5. References

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