

Device Physics and Modeling of Multiple Quantum Well Infrared Photodetectors

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In this paper we present the picture of the physical effects in the Quantum Well Infrared Photodetectors (QWIPs) utilizing intersubband electron transitions. Our study is based on the numerical model, which allows one to find the distributions of the physical quantities in the QWIP structure and to calculate the external device characteristics. The operation of QWIP is associated with the nonuniform distribution of the potential and other related physical quantities. We show that contact and distributed effects play an important role in determining the operation and characteristics of the QWIPs.

1 Introduction

There has been a strong interest in Quantum Well Infrared Photodetectors (QWIPs) utilizing intersubband transitions.¹⁾ The physics of these devices is very interesting and, in spite of numerous experimental and theoretical studies, is not fully understood. In particular, the contact and distributed effects are disregarded by conventional models of QWIPs.^{2,3)} However, as we discussed in ref. 3, these effects can be of great importance in determining the electrical and optical properties of the QWIPs. In the present paper, extending our previous studies,^{2,3)} we present the picture of physical processes in QWIPs. We study, using a proposed distributed model of QWIP, the important physical effects, such as electron injection, transport, and capture/emission, in a self-consistent manner, and demonstrate their influence on external device characteristics.

2 Device Structure and Model

The QWIPs under consideration comprise a QW structure, sandwiched between the emitter and collector barriers, followed by contact layers heavily doped by donors. The QW structure includes heavily doped narrow-gap QWs separated by thick undoped wide-gap barriers. It is supposed that QWs contain only one bound level. The following effects are taken into account in our model (see Fig. 1): injection of electrons from the emitter due to thermionically assisted tunneling, transport of electrons excited over the barriers in the QW region, capture of continuum states electrons by the QWs, thermo- and photoemission of bound electrons from the QWs into the continuum, recharging of the QWs, and associated nonuniform distribution of the potential and other physical quantities in the QWIP.

The model of the QWIP is described by coupled equations, including Poisson's equation, current continuity equation for continuum states electrons, and a rate equation coupling the bound state and continuum states electrons. We neglect the tunneling coupling be-

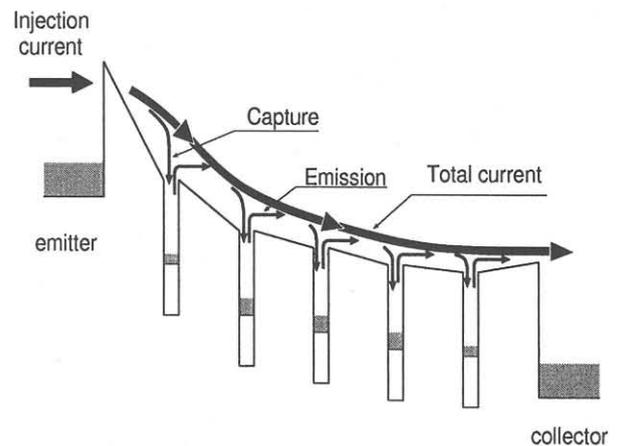


Figure 1: Schematic diagram of physical processes in QWIP.

tween the QWs due to the large thickness of the barriers. The electron capture by and emission from the QWs are described phenomenologically, in terms of the QW recombination velocity and thermionic emission time. Calculation of the emission time is based on the following assumptions: balance of the capture and emission under equilibrium, and exponential dependence of the emission current on the Fermi energy of bound electrons and electric field (due to the lowering of the effective barrier for thermionic emission). Transport of continuum states electrons is described in the frame of the drift-diffusion model, with the field-dependent mobility

and diffusion coefficient. The self-consistent solution of the model equations allows us to find the distribution of the physical quantities in the QWIP structure, the external characteristics, and to study the role and interplay of physical processes in the QWIPs. The results presented below were obtained for GaAs/Al_{0.25}Ga_{0.75}As QWIP with five QWs, with QW width of 40 Å, barrier width 500 Å, and doping 10¹⁸ cm⁻³ in the QWs and contacts. We assumed photoionization cross-section $\sigma=2\times 10^{-15}$ cm² and photon flux $I=2.5\times 10^{19}$ cm⁻²s⁻¹ for illumination conditions.

3 Physical Processes in QWIP

With application of the voltage to the QWIP, electric field appears in the QW structure. In steady state, the electron current, which is due to the continuum states electrons, is constant throughout the QW region. This condition can not be satisfied with the uniform electric field distribution in the QW region, as illustrated in Fig. 2.

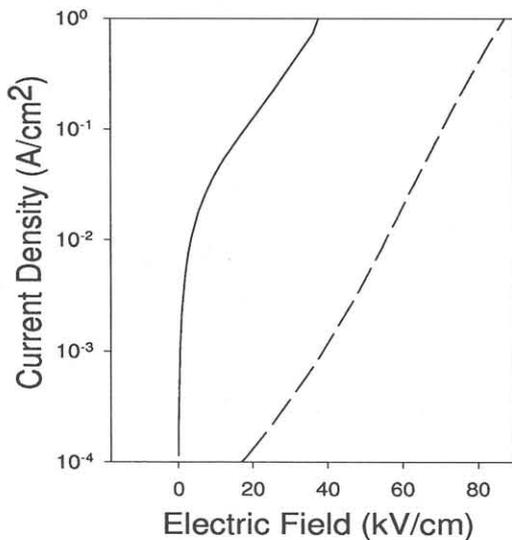


Figure 2: Electric field dependence of injection current of the emitter contact (dashed line) and drift current of the bulk QW region (solid line).

The difference in current-voltage characteristics of the injecting emitter contact and the bulk QW structure is the reason for the nonuniform distribution of the electric field in the QWIP. Our results show that the domain of the high electric field is formed near the emitter, controlling the tunneling electron injection (see Fig. 3). This domain extends over a few barriers close to the emitter contact. In the rest of the QW structure, the electric field is low and almost constant. Both the high electric field in the emitter contact and low field in the bulk of the QW structure differ significantly from the average electric field (Fig. 3).

The nonuniformity of the electric field is due to the recharging of the QWs. The first few QWs near the

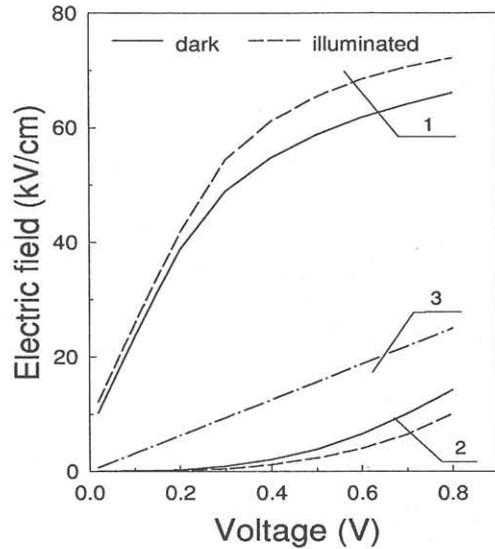


Figure 3: Electric field dependence on applied voltage (1 – field in the emitter barrier, 2 – in the bulk of the QW structure, 3 – average electric field).

emitter are depleted by the electrons (see Fig. 4). The positive charge build-up in these QWs with applied voltage is responsible for the formation of the high field domain and enhancement of electron injection from the emitter.

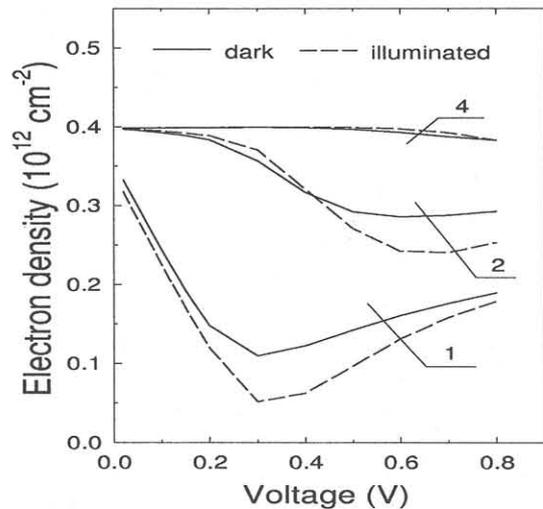


Figure 4: Bound electron density versus voltage (index corresponds to a number of the QW, counted from the emitter).

Under illumination, the enhanced emission of bound electrons from the QWs into the continuum should be compensated by the capture of continuum states electrons. This gives rise to an increase of the concentration of electrons above barriers and, consequently, to the increase of the electron current. The underlying

physical mechanism is the redistribution of the potential in the QW structure under illumination, with the enhancement of the electric field in the emitter barrier to provide additional electron injection (Fig. 3). This is accompanied by the recharging of the QWs (Fig. 4). Thus, the contact and distributed physical effects play an important role in operation of QWIP both in dark regime and under illumination.

4 Device Characteristics

The calculated external device characteristics reflect the features of the distributions of internal physical quantities (see Figs. 5 and 6).

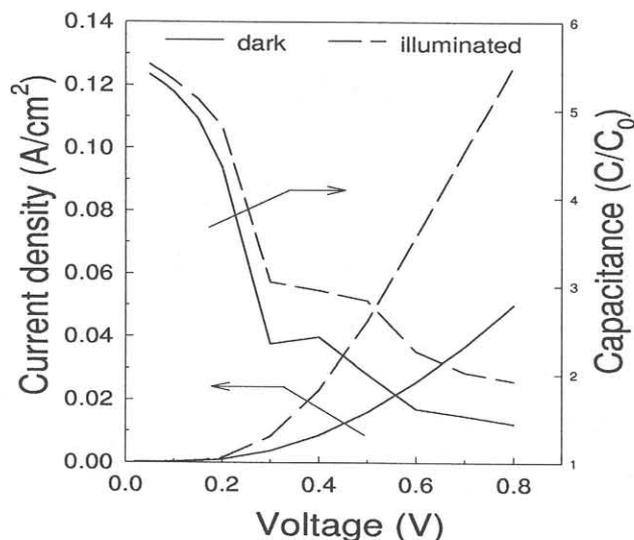


Figure 5: Current density and quasistatic capacitance of QWIP (C_0 is the geometric capacitance of the QWIP).

At low voltage, the current is low, and differential resistance is high, until the domain of high field is formed near the emitter. In this regime, the capacitance of the QWIP is high and corresponds to the emitter barrier width. Once the high field domain is formed, the current increases strongly with voltage, due to the increase of the electric field in the bulk of the QW region. This is accompanied by the decrease of the differential resistance of the QWIP and increase of the photocurrent gain, defined as the ratio of the photocurrent to the current of the direct photoexcitation. Under the influence of infrared radiation, the extra injection of electrons from the emitter due to the modulation of the contact electric field and recharging of the QWs, give rise to a photocurrent and photocapacitance of the QWIP.

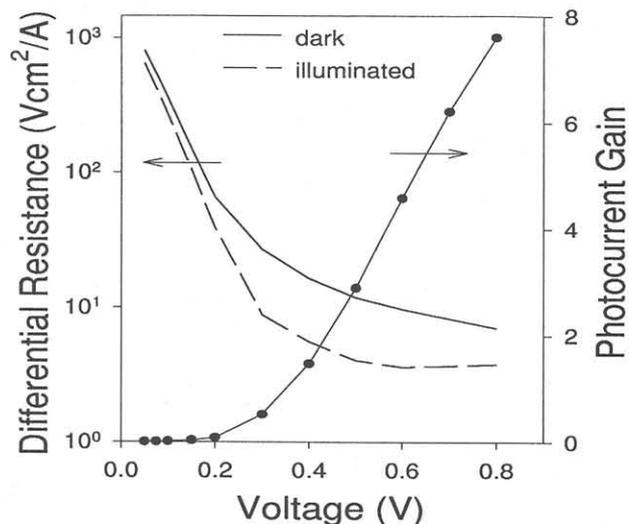


Figure 6: Differential resistance and photocurrent gain of the QWIP.

5 Conclusion

Physical effects in the QWIPs based on intersubband electron transitions were discussed and studied quantitatively using a proposed numerical model. The operation of the QWIPs is associated with the nonuniform distribution of the potential in the QWIP structure due to the recharging of the QWs, and formation of the high field domain near the emitter. The photodetection mechanism is due to the redistribution of the potential under the influence of infrared radiation. We showed that the contact and distributed effects play an important role in determining the QWIPs characteristics.

References

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