THE EFFECT OF THE FIRST BARRIER THICKNESS ON RESONANCE TUNNELLING AND CARRIER ACCUMULATION IN UNDOPED SINGLE QUANTUM WELL INFRARED PHOTODETECTORS

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ABSTRACT

The electrical behaviour of an undoped, MBE-grown, asymmetric thickness-double barrier single quantum well (QW) infrared photodetector structures were studied. The structures consisted of 100-200 Å thick $Al_{0.27}Ga_{0.73}As$ emitter barrier, a 40 Å thick GaAs quantum well (QW) and a 500 Å thick $Al_{0.27}Ga_{0.73}As$ collector barrier. In order to describe the current generation mechanisms, the resonance current and the non-resonance current from emitter contact to QW, and the field emission current from the QW were simulated by numerical calculations. Calculated and the measured currents were in good agreement. Our result showed that the QW carrier density increased with reduced emitter barrier thickness enhancing the detector performance but at the cost of increased noise levels with dark current.

INTRODUCTION

With increasing interest in physics and potential application of resonance tunnelling (RT) devices in microelectronics and optoelectronics, intensive studies on these structures have been carried out during the past several years. However, less attention has been devoted to asymmetric thickness-double barrier single quantum well (QW) RT structures. These heterostructures are particularly interesting in the context of quantum well infrared photodetectors (QWIP). The optical properties of such a structure were first studied by Liu et al (1). The I-V relation, infrared responsivity and optical gain were analysed by Bandara et al (2).

In such undoped QW structures the empty ground state is populated by the resonance current. Therefore the optical response is strongly dependent on bias voltage. When the collector barrier thickness is large there is no resonance tunnelling from the QW to the collector contact. To understand the nature of the resonance tunnelling in such structures, we investigated the current generation mechanisms and numerically simulated the transport by using the specific parameters of the structure. We have studied the current-voltage characteristics at 77 K for three structures with $Al_{0.27}Ga_{0.73}As$ emitter barrier thicknesses 100 Å, 150 Å and 200 Å, 40 Å thick GaAs QW and 500 Å thick $Al_{0.27}Ga_{0.73}As$ collector barrier. Our findings showed that both carrier accumulation in the QW region and the resonance current increased with reduced emitter barrier thickness.

EXPERIMENTAL

The forward bias band structure is shown schematically in the inset of the Fig. 1. The structure was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. First a 1 µm thick GaAs contact layer ($n=1.4x10^{18}$ cm^{-3}) was grown followed by 500 Å thick $Al_{0.27}Ga_{0.73}As$, 40 Å GaAs and 150 Å $Al_{0.27}Ga_{0.73}As$. Finally a 0.5 µm thick GaAs ($n=1.4x10^{18}$ cm^{-3}) contact layer was deposited. After the growth, 200 µm wide mesas were made by standard lithography and etching processes. Contacts (Au-Ge) were evaporated on top of the mesa and on the bottom contact layer. The Ohmic metal contacts were bonded by thin Au-wires. The dark current was measured at 77 K for the bias voltage interval 0 to 500 mV in 10 mV increment steps.

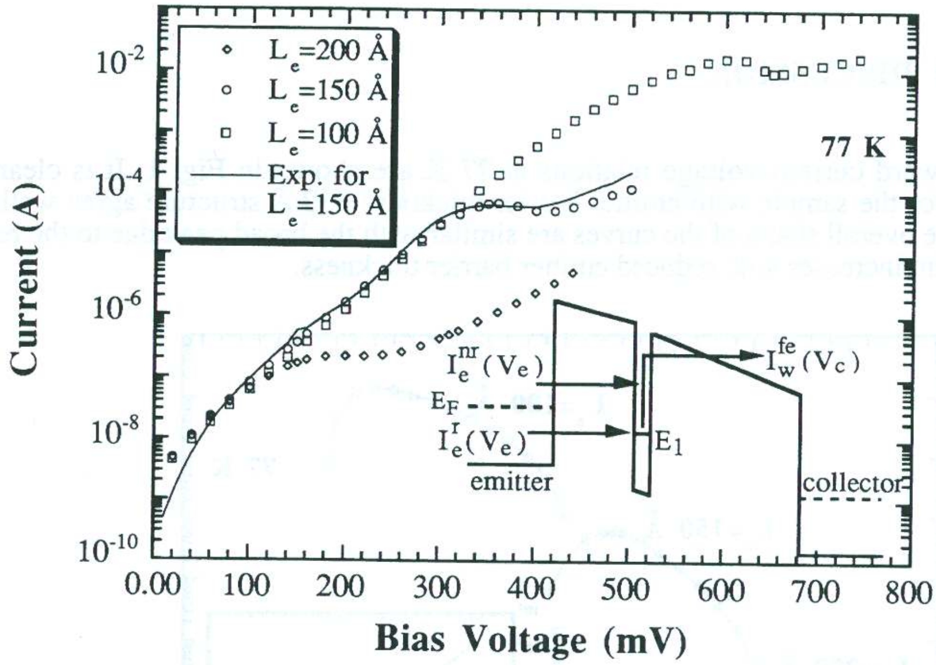

Fig. 1. The calculated forward current-voltage dependence for all structures. The solid line represents the experimental curve for the structure with 150 Å emitter barrier thickness. The inset illustrates the forward bias band structure and the current components.

THEORY

The total current and the position of Fermi energy in the QW are calculated by equating the rate of electron injection into the QW with the emission rate from it. These injected electrons are treated as the resonance tunnelling current $I_e^r(V_e)$ and non-resonance/thermally assisted tunnelling current $I_e^{nr}(V_e)$ from the emitter contact to the QW. Due to the thick collector barrier there is no resonance current from QW to the collector, except the two dimensional field emission current $I_w^{fe}(V_c)$ from the QW which is treated as the rate of emission from the QW. The total current through the structure can be written as

$$I(V_e,V_c)=I_e^r(V_e)+I_e^{nr}(V_e)=I_w^{fe}(V_c)\ , \qquad (1)$$

where V_e, and V_c are the voltage drops across the emitter and collector barrier, respectively. These current components and the band bending are illustrated in the inset of Fig. 1. The equations for the thermally assisted tunnelling current from the emitter and field emission current from the QW are the same used by Rosencher et al (3) and Bandara et al (2), (4). The resonance current formula is derived by the "Transfer Hamiltonian formalism" considering tunnelling from a three dimensional gas in the emitter to the two dimensional QW ground state (5). In principle the resonance condition is fulfilled when the QW energy state is aligned with the Fermi level in the contact. However, we consider the system to be in resonance as long as the conduction band electrons in the emitter contact layer can tunnel to the QW energy state. We also assume that the QW is populated only by electrons from the resonance current. The average three dimensional electron density in the QW is given by

$$n = \left(\frac{mk_B T}{\pi\hbar^2 L_w}\right)\ln\left(1+\exp\left(E_F^{qw}\Big/k_B T\right)\right). \qquad (2)$$

Here L_W and E_F^{qw} are the thickness and the Fermi level respectively of the QW. The other symbols have their usual meaning.

RESULTS AND DISCUSSION

The simulated forward current-voltage relations at 77 K are shown in Fig. 1. It is clear that the measured current for the sample with emitter barrier thickness 150 Å structure agree well with the calculated data. The overall shape of the curves are similar with the broad peak due to the resonance. In general the current increases with reduced emitter barrier thickness.

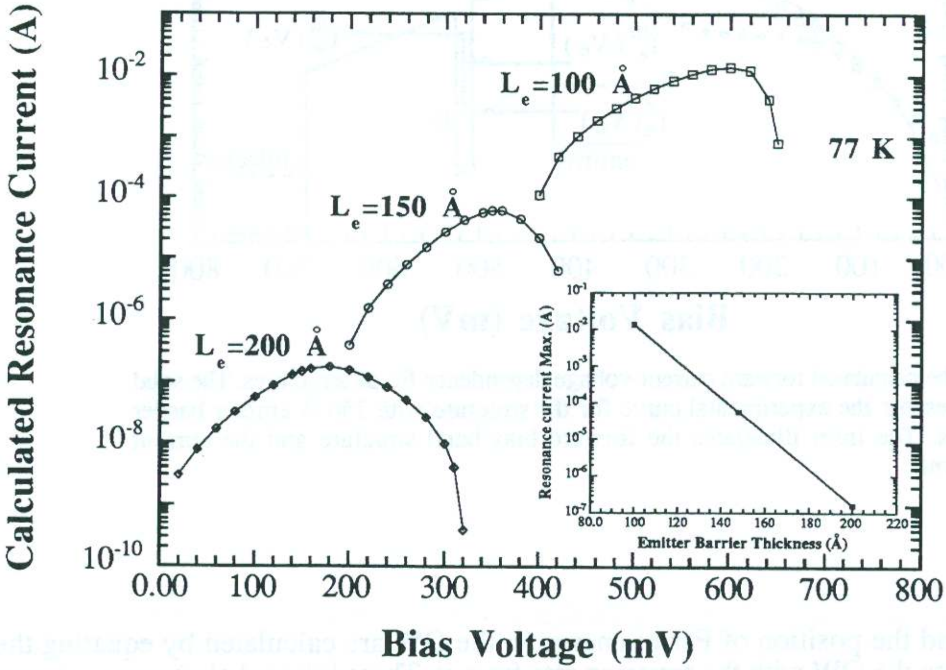

Fig. 2. The calculated resonance current as a function of the external bias voltage. The inset shows the exponential variation of resonance current maximum with the emitter barrier thickness.

The calculated dependence of the resonance current on the bias are shown in Fig. 2 with a broad maximum. As shown, this variation is responsible for current peak. The non-resonance contribution increases with bias and hence the total current is increased. A limitation to the resonance current is the charge accumulated in the QW ground state. This calculated carrier accumulations are shown in Fig. 3. It is very clear that according to the inset graphs in Figs. 2 and 3 the resonance current peak position and the maximum charge accumulation in the QW increase exponentially with reduced emitter barrier thickness.

It is evident that the findings of special structures that limits the dark current but still allow the resonance, are crucial for realisation of QWIP operation above the cooling temperatures.

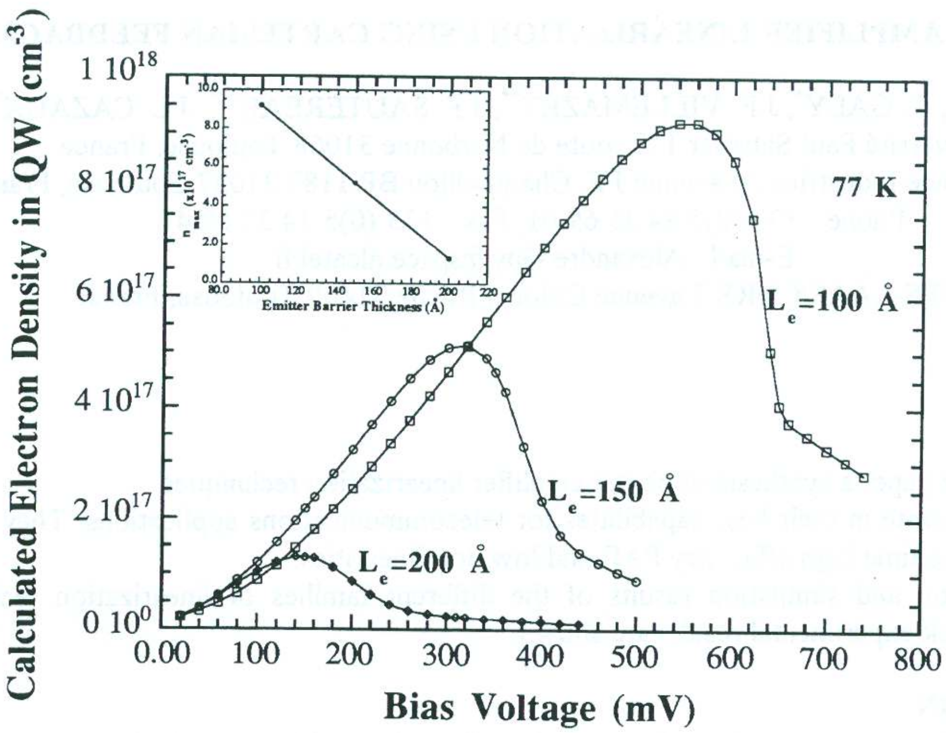

Fig. 3. The calculated electron accumulation in the well region as a function of the bias voltage. The inset shows the carrier density maximum with the emitter barrier thickness.

CONCLUSION

Our theoretical model provides a good agreement between the simulated and measured current within several orders of magnitudes as a function of bias. This indicates that the carrier transport process through such QW structures is due to the combined effect of resonance and non-resonance tunnelling as well as field emission. The resonance current and the carrier accumulation both increase exponentially with reduced emitter barrier thickness. The performance of infrared detectors based on such structures could be enhanced with thin emitter barriers due to the high electron accumulations in QW but at the cost of increased noise levels with dark current.

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