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A Self-Consistent Analysis of the Coherency of Hot Electron Emitters

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The energy spectrum of emitted electrons from a single barrier is analysed taking into account the quantised levels of an accumulation layer. A self-consistent model is developed which solves Poisson's equation, the continuity equation, Schrödinger's equation and the heat equation. The relationship between the population of the quantised levels, the energy relaxation time and the tunnelling probability is formulated. It is shown that the ratio between the 2D and 3D current components can be optimised and a new device is proposed which effectively removes the three dimensional component.

1. INTRODUCTION.

For the next generation of transistors, devices based on the wave properties of electrons are both interesting and important[1]. To realise such structures the coherency of the electron beam is of critical importance. For devices based on the wave nature of electrons it is necessary to reduce the energy width, which is determined by both scattering during propagation and the characteristics of the emitter. One of the simplest emitters is a single heterobarrier structure and the energy spread of tunnelled electrons from this structure may be obtained in a straightforward way by using the Tsu-Esaki formula[2]. However in reality an accumulation layer builds up due to band bending at the heterointerface. If the band-bending is strong enough then quantised levels can exist and electrons emitted from these levels will have their energies quantised in the direction of propagation. It is the aim of this paper to investigate the relative proportions of quantised and unquantised current from a single heterobarrier structure and to consider methods to improve the performance.

2. THE MODEL

Figure 1 shows the principle behind the emitter. As the voltage is increased so the band bending at heterobarrier becomes more significant. At a certain voltage there is sufficient band bending to produce quantisation in the quantum well. As the voltage is further increased the current is split into 2D and 3D components.

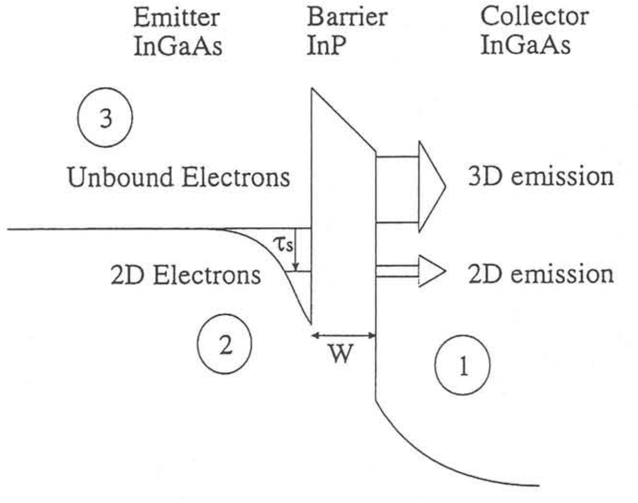

Fig 1. Principle of Operation

To calculate the ratio between the two components the following equations must be solved. Schrödinger's equation to calculate the eigenfunctions of the electron wave, Poisson's equation to calculate the potential distribution, the continuity equation to calculate the quasi Fermi level and the heat equation to calculate the heat distribution within the device. The device is split up into 2 distinct parts using the quantum window method[3]. This enables the parts of the device outside the quantum window to be analysed using conventional carrier statistics. It acts as a computational tool as it provides a method to consider Schrödinger's equation within only a specific region of the device. Within the quantum mechanical part of the device the current must be calculated using a modified Tsu-Esaki formula, modified in such a way so as to include both 2D and 3D components and the effects of a non-equilibrium distribution. To do this a modified Fermi-Dirac distribution is proposed where the thermal equilibrium Fermi function in the well f_2 is multiplied by a factor f^*,

$$f^* = \frac{\frac{\tau_{res}}{\tau_s} f_3 g_3 + T f_1 g_1}{\frac{\tau_{res}}{\tau_s} f_3 g_3 + T f_2 g_1} \qquad (1)$$

where τ_{res} is the resident time of an electron above the quantum well, τ_s is the scattering time into the quantum well, T is the tunnelling probability out of the quantum well, f and g are the Fermi function and density of states respectively, the subscripts of which refer to fig 1. Equation 1 can be derived from the rate equations in and out of the quantum well. In the case of no applied bias equation (1) reduces to 1 as the occupation probabilities f_1 and f_2 must be identical. In the case of a positive bias (states in 1 are unoccupied) equation (1) may be approximated by

$$f^* = \frac{1}{1 + \frac{T f_2 g_1}{\frac{\tau_{res}}{\tau_s} f_3 g_3}} \qquad (2)$$

In the case that the barrier is very thick T becomes very low and equation (1) tends to 1, i.e. the system is in thermal equilibrium. Also in the case that τ_s is very short then again the system tends to its equilibrium distribution. The only unknown parameter in equation (1) is the scattering time τ_s and in line with recent experimental results a value of 1ps is used for all quantised levels[4]. In addition to the above phase-breaking processes within the accumulation layer must be considered as they can significantly broaden the energy spread of the 2D electrons. This is achieved via the use of a Lorentzian broadening model[5].

3. COMPUTATIONAL ASPECTS

The Control Region Approximation (CRA)[6]is used in the solution to Poisson's equation, the continuity equation and the heat equation. The non linear equation set is linearised using the Newton Raphson method and the underlying linear equation set is asymmetric and solved using the Conjugate Gradient Squared Method (CGS). A sparse storage scheme is used to store all the assembled matrices and to carry out the linear algebra. To calculate the energy levels in the accumulation layer quantum well the transfer matrix method is used[7] where, the potential profile is discretised and, using the correct boundary conditions between nodes, the transmission coefficient may be calculated for any energy. The energy range is swept and the energy levels may be determined from the maximums in the transmission coefficient profile.

4. RESULTS AND DISCUSSION

The following results are for a device of barrier width 6nm, a temperature of 77K and an emitter doping level of $1 \times 10^{16} cm^{-3}$. Figure 2 shows typical energy spectrums for three different scattering times into the quantum well from the 3D continuum. There is a fundamental difference between phase breaking within the well and scattering into the well. The total 2D current is unaffected by phase breaking within the well, only the peak of the current distribution increases or decreases. For scattering into the well when the scattering time increases the total 2D current is reduced. The reason the 2D current is reduced is due to the electron distribution in the quantum well moving away from its equilibrium Fermi-Dirac distribution. This may be explained in terms of electrons in the quantum well being replaced at a much slower rate and hence the quantum well remains relatively unoccupied.

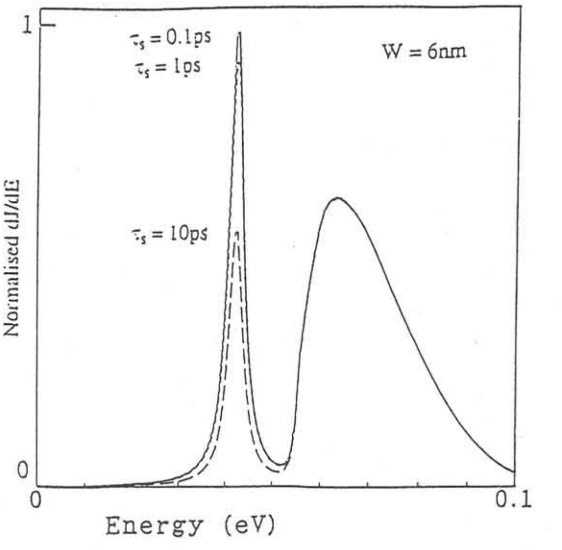

Fig 2. Energy Spectrum/ Scattering time τ_s

Figure 3 shows the ratio of 2D current to the total current at a range of voltages and barrier thicknesses. At low voltages the band bending is insufficient to produce a 2D component. However at high voltages the occupancy of the well is very low due to the high escape rate from the well. Therefore there is an optimum voltage which will vary depending on the barrier thickness, doping level and material. In this case the optimum set of parameters is at a barrier thickness of 4nm and an applied voltage of 0.6V. To achieve a higher ratio the doping in the emitter could be reduced, lowering the Fermi-level. However, to achieve a sufficiently high coherency the doping level would become too low to produce a significant current. One method to overcome this is shown in figure 4 where the single barrier is connected to 2 contacts at the lateral edges of the device. This ensures that the quantum well still forms at the barrier, that the Fermi-level is sufficiently low to ensure that the 3D current is very low but that the 2D current can still flow due to lateral contacts acting as reservoirs for the 2D electrons. Simulations indicate that using this structure the 3D component can be effectively removed.

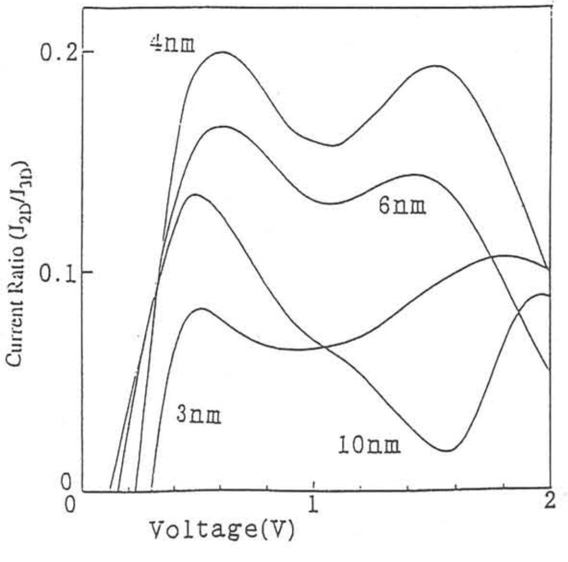

Fig 3. Current Discrimination Ratio

5. SUMMARY

A numerical method has been developed to consider the emission of electrons from a single barrier. It is shown that at an applied bias the tunnelling current is composed of 2 components, a 3D tunnelling current and a 2D quantised tunnelling current. The ratio of these components is calculated and it is shown that the ratio can be optimised by the correct choice of the width of the barrier and applied voltage. A new device with two lateral contacts attached to the accumulation layer is proposed which effectively removes the 3D component, thus providing a high degree of coherency in the direction of propagation.

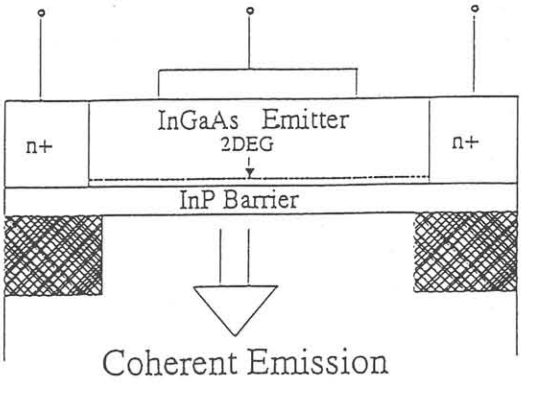

Fig 4. Proposal for new device

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