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NANO-SCALE VERTICAL FIELD EFFECT TRANSISTOR REALIZED BY WAVE FUNCTION OVERLAP IN SUPERLATTICE.

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Abstract

A vertical field-effect transistor of nano-scale dimension has been theoretically realized based on the principle of wave function overlap in superlattice which causes an enhancement in the tunnel current. The mini band structure of GaAs/GaAlAs superlattice favor the condition for substantial increase in tunnel current and paves the path for the design of such a device.

I. INTRODUCTION

In nano-scale dimensions the emergence of quantum transistors have attracted considerable research interests in this direction and these transistors have superseded in performance the conventional transistors which fail to operate in the quantum regime [1].In this paper, we present a theoretical model for a vertical field-effect transistor, where the adjustable subband energy of a quantum well changes the vertical extent and overlap of its wave function with adjacent well. This quantum transistor does not utilize tunnel resonance of aligned subbands [2-4] or single electron characteristics in quantum dots [5]. Moreover, this type of device can be operated down to nano-scale dimensions in suitable material [6]. This transistor is given the name wave- function extension transistor (WET). The mobility and gain characteristics of GaAlAs/GaAs superlattice laser has also been studied by the authors [7].

II. THEORETICAL MODEL

A binary alloy superlattice such as GaAlAs/GaAs is formed by stacking of alternate layers of GaAlAs (labeled i=1) and GaAs (i=2) of layer thickness d_1 and d_2 respectively, creating a periodicity in the growth direction with periodicity length $D = d_1+d_2$.The conduction band profile of this system is effectively an array of GaAs quantum wells with layers of GaAlAs forming an array of barriers of energy V_0. We consider a fixed barrier thickness d_1=10nm of $Ga_{0.7}Al_{0.3}As$, and investigate the variation of the properties of the system with the varying well-width d_2 .The motion of conduction electrons is subject to the following potential

$$V(z) = \sum_{|n|=1}^{\infty} V_0\left(\theta(z - z_n) - \theta(z - z_n - d_1)\right) \quad (1)$$

Where energy is measured relative to the bottom of conduction band of GaAs. θ is the unit step function and z_n is defined by

$$z_n = (n-1)D\,; \qquad |n| \geq 1 \qquad (2)$$

The index n is such that (2n-1) labels the layers of component 1 and 2n for layers of component 2; n is the index of the superlattice cell defined for one layer of each material.

The coordinates are such that z=0 plane coincides with the bottom of layer 1. The hamiltonian eigenvalue equation for electrons in the superlattice is given by

$$H_g^0\psi(x) = \left(-\frac{\hbar^2}{2m^*(z)} + V(z)\right)\psi = E\psi(x) \qquad (3)$$

where $m^*(z) = m_1^*$; in layers (2n-1)
$= m_2^*$ in layers 2n (4)
n = 1, 2, …

With m_1^* and m_2^* the effective masses for electrons. The solution of eq (3) is written considering the translational invariance parallel to the layers as

$$\psi(x) = \eta(z)e^{iK\|.x\|} \qquad (5)$$

Where we have written $x = (x\|, z)$ and $K_{\|}$ is an two dimensional wave vector component parallel to the layers. The solution of (3) are written in the from

$$\eta(z) = A_{2n-1}e^{-iK_1(Z-Z_n)} + B_{2n-1}e^{-iK_1(Z-Z_n)}; \qquad \text{layer } 2n-1$$

$$= A_{2n}e^{-iK_2(Z-Z_n)} + B_{2n}e^{-iK_2(Z-Z_n)}; \qquad \text{layer } 2n \qquad (6)$$

Where the A's and B's are constants characterizing the layer and

$$K_1^2 = \frac{2m_1^*}{\hbar^2}(E - V_0) - K_{||}^2$$
$$K_2^2 = \frac{2m_2^*}{\hbar^2}E - K_{||}^2 \qquad (7)$$

Where K_1 and K_2 are (in general) complex. The boundary conditions for the problem are

$$\Psi \text{ and } \frac{1}{m^*}\left(\frac{\delta\psi}{\delta z}\right) \text{continuous} \qquad (8)$$

at every interface of the superlattice. The periodicity of the superlattice is taken in to account by applying Bloch's theorem which give the following relations

$$A_m = g\,A_{m-2}$$
$$B_m = g\,B_{m-2} \qquad (9)$$
$$|\,m\,| = 0, 1, 2, \ldots$$

with,

$$g = e^{iQD} \qquad (10)$$

The dispersion relation of superlattice electrons is finally obtained as follows [8]:

$$\cos QD = \cos K_1d_1 \cos K_2d_2 - 0.5\,(Z + 1/Z) \sin K_1d_1 \sin K_2d_2 \qquad (11)$$

Here Q and K_{11} are perpendicular and parallel components of the electronic wave vector.

III. RESULTS AND DISCUSSION

We have taken the parameters for $Ga_{0.7}Al_{0.3}As$/GaAssuperlattice as V_0 = 0.19eV, m_1^* = 0.089m_e and m_2^* = 0.063m_e, where m_e is the electron mass. Figure 1 shows the variation of the electronic subband minima with the well-width d_2 for the $Ga_{0.7}Al_{0.3}As$/GaAs superlattice, for fixed barrier width d_1 = 10nm, computed using eq.(11) with K_{11} = 0. The tunneling probability between the successive subbands are calculated using Bardeen's formalism [9]. The overlap of wave functions between the bands as shown in Figure 2 , cause a large increase in the tunnel current. The tunnel current is proportional to the square root of the electron energy, i.e., $(E)^{1/2}$ and therefore it increases for higher subband energy as marked by the levels 1, 2, 3, in the figure 1.

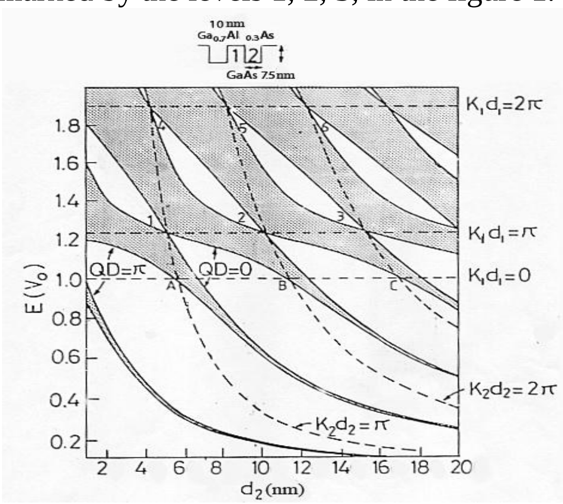

Figure 1: Band structure variation with well width d_2 for fixed barrier width d_1 =10nm for GaAs/$Ga_{0.7}Al_{0.3}$ As superlattice, all other parameters are as described in the text.

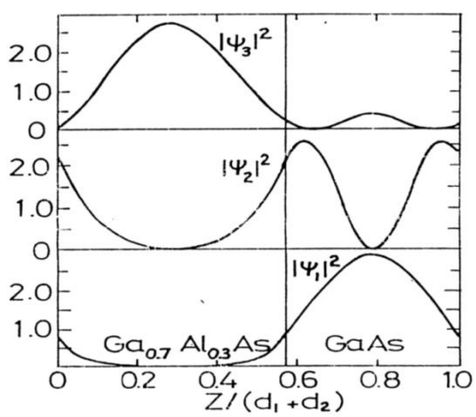

Figure. 2: Probability distributions of the ground state and the first and second excited states in GaAs/$Ga_{0.7}Al_{0.3}$ As superlattice with d_1 =10nm and d_2=7.5nm. Other parameters are described in the text.

Thus it is obvious that the array of mini bands in the GaAs/ $Ga_{0.7}Al_{0.3}As$ superlattice as shown in the figure 1, will cause enhanced tunneling between the consecutive bands and thus show the perfect promise for the design of the WET. The design model of the quantum vertical field effect transistor is realized considering four layers of the superlattice and is shown in the figure 3.

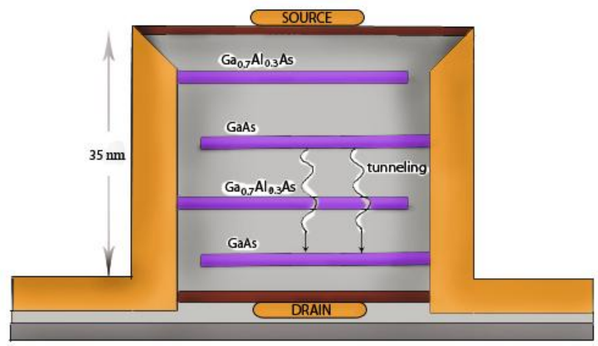

Figure 3: Design model for WET device with $Ga_{0.7}Al_{0.3}As$/GaAs superlattice having double barriers of $Ga_{0.7}Al_{0.3}As$, each of 10nm and two wells of GaAs each of 7.5nm width.

The four layers consist of double layers of barrier of $Ga_{0.7}Al_{0.3}As$ each of width 10nm with two layers of GaAs wells of 7.5nm width, where tunneling of electrons occur between two alternate GaAs wells.

IV. CONCLUSION

In the present paper, the authors have demonstrated from a theoretical viewpoint that GaAs/ $Ga_{0.7}Al_{0.3}As$ superlattice is the suitable material for the design of the WET. Likewise in the conventional transistors, application of bias and gate voltage would control the current –voltage characteristics of the WETs. The design model of the quantum vertical field effect transistor as shown in the figure 3, would throw significant light in understanding the physics of vertical transport phenomena in superlattices.

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