Switching Characteristics of Voltage Controlled Electron Waveguides

Shalini Garg, R. K. Sinha* AND K.L.Deori

Department of Applied Physics, Delhi College of Engineering, Faculty of Technology, University of Delhi.E-mail: - sgupta90@yahoo.com ; dr_rk_sinha@yahoo.com *Phone +91-11-7853915

Abstract

We present the switching charac-teristics of voltage controlled electron waveguide. This quantum-effect electronic device behaves as a current switch. The switching parameters varies in accordance with the mole fraction x of the semiconductor heterostructure GaAs/$Ga_{1-x}Al_xAs$. Since the effective mass of the electron , m_e , is controlled through the alloy composition x in the semiconductor heterostructure GaAs/$Ga_{1-x}Al_xAs$, zero transfer/ complete transfer of the electron wave packet initially injected into this device through one of the waveguides , can be obtained at different gate voltages .

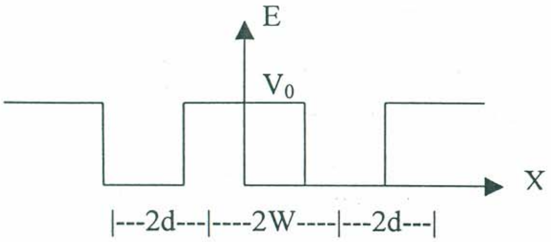
(Keywords :Electron waveguide/ Transfer length/ Transfer coefficient)

Introduction

The basic building block of an electron waveguide device is the electron waveguide, which is a thin wire to which electrons are confined by such a potential that the electrons can move freely only in one dimension. The most important characteristic of electron waveguides is their width be comparable to the deBroglie wavelength in the material. Owing to the recent advances of the semiconductor technologies, it has been possible to reduce the critical dimensions of the devices to below the mean free path of the electrons and to increase the mean free path itself by suppressing scattering and using a small-electron-effective mass material. Like light, electron waves[1] can be guided in quantum well channels. The guided electron waves in adjacent channels can be coupled strongly or weakly depending on the thickness and/or the barrier height of the coupling layer. Such an electron wave coupling function opens up interesting and potentially important opportunities for device application[2].

The alloy system $GaAs/Ga_{1-x}Al_xAs$ is potentially of great importance for many high speed electronics and optoelectronic devices, because the lattice parameter difference between $GaAs$ and $Ga_{1-x}Al_xAs$ $(0\leq x\leq 1.0)^3$ is very small (less than 0.15% at 300K), which promises an insignificant concentration of undesirable interface states. The effective mass, which is strongly connected with the carrier mobility, is known to be one of the most important device parameters. Electrons are charged particles with a finite mass and consequently possess a nonlinear dispersion relation.

Switching parameters



We consider two electron waveguides that over a certain length come in very close proximity to each other. We refer to the two waveguides as source waveguide and drain waveguide. The electrons are confined in two dimensions (x and y) but are free to move along the third one (z). A narrow metal gate runs over the entire coupler length which, through an applied gate voltage , can control the energy barrier height between the two waveguides. The strength of the coupling between the two waveguides can therefore be modulated by the field-effect action of the gate. The ohmic contacts to the waveguides act as large reservoirs for electrons. If the coupler length is smaller than the electron phase coherence length, electrons can retain phase coherence while traveling through the active region. The coupled system consists of a symmetric mode and an anti-symmetric mode. The symmetric modes pumps the anti-symmetric modes and vice versa. Exciting the input of the source waveguide selects a proper combination of these two modes which results in the periodic transfer of electron probability density back and forth between the source and drain waveguides as the packet travels down the coupler. At a certain length, L_t called the transfer length, complete transfer of probability density to the drain waveguide is achieved. So, the transfer length is the length of the coupled region required for complete probability density transfer from the source to the drain waveguide. This transfer length is a function of the strength of the potential barrier existing between the two quantum waveguides. A higher or thicker barrier requires longer transfer lengths. Beyond L_t, the probability density starts being transferred back to the source waveguide. For a length exactly equal to $2L_t$, complete probability density is now back again at the source waveguide and so on in a periodic manner. So, the barrier can be modulated by the field-effect action of the gate and, for a given physical coupler length L_c, complete transfer or negligible transfer can be achieved by varying the applied gate voltage .In this manner, the device behaves as a voltage-controlled current switch.

Under the weak coupling condition[4], the electron wavefunctions in the two waveguides are of the form

$$\psi_s(x,y,z)=u_s(x)v_s(y)s(z)e^{-jk_{sz}z} \tag{1}$$

$$\psi_d(x,y,z)=u_d(x)v_d(y)d(z)e^{-jk_{dz}z} \tag{2}$$

where u_s, v_s, u_d, v_d are the solutions of the uncoupled waveguides in the x and y directions. Confining potential is denoted by V_x. k_z represents the electron wave number along the z axis. In the case of negligible coupling, $s(z)$ and $d(z)$ do not depend on z and will be independent of each other. The wave function for the coupled-mode system is $\psi_c=\psi_s+\psi_d$. Substitute this into the time independent Schrodinger equation for a completely symmetric system. Under the normalized initial condition i.e $a(0) = 1$ and $b(0) = 0$, the amplitudes in the direction of propagation become

$$s(z) = \cos(\kappa z) \quad (3)$$

$$d(z) = -\sin(\kappa z) \quad (4)$$

where κ is the coupling coefficient.

$$\kappa = \frac{m^*}{\hbar k_z} \int_{-\infty}^{\infty} u_a^* V_x' u_b \, dx$$

The transfer length L_t, where the amplitude of the wavefunction in the source waveguide becomes zero while in the drain waveguide it becomes unity is given by

$$L_t = \pi / 2\kappa \quad (5)$$

For adequate operation the device L_t has to be smaller than the electron coherence length, which can be as high as $5\mu m$. This imposes a limit to the strength of the barrier that can exist between the waveguides. The transfer coefficient T_c is given by

$$T_c = |d(z = L_c|^2 / |s(z = 0)|^2 \quad (6)$$

As a realistic example, $GaAs / Ga_{1-x}Al_x As$ heterostructure system[5] can be used for the device where we vary the mole fraction x within limits and calculate the corresponding switching parameters. We consider two 500 Å - wide, 5: m long electron waveguides with finite square well profiles separated by 300Å[6]. κ and L_t are calculated as a function of the barrier thickness and barrier height. E_x=2.2 meV and k_z = 8.4 x 10^5 cm^{-1} V_b is the barrier height in the x direction.

Switching Characteristics

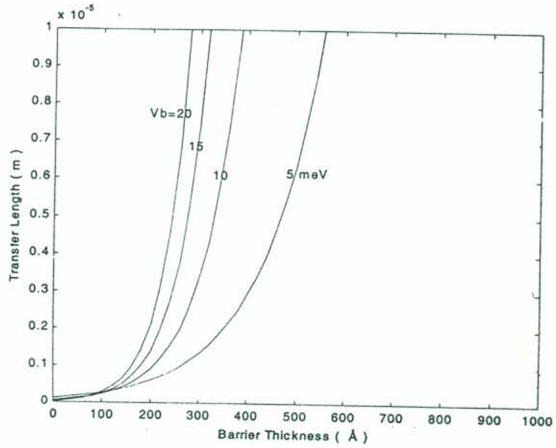


Fig. 1. indicates that as the barrier thickness or the barrier height increases, the coupling between the waveguides becomes weaker and the required L_t increases very quickly. For adequate operation of the device the transfer length has to be smaller than the electron coherence length, which can be as high as 5: m.

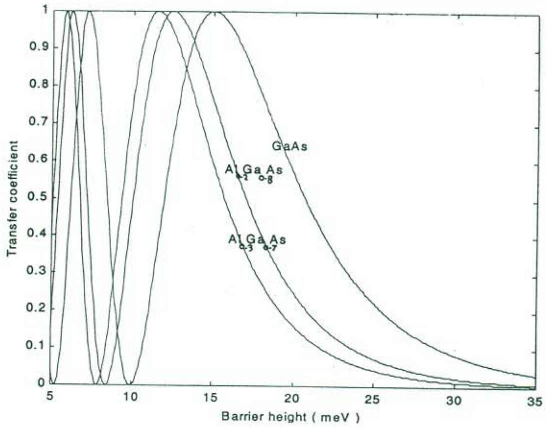


Fig. 2. shows the transfer coefficient as a function of the barrier height. Observations made from the graph are tabulated in Table1.

Alloy composition	Complete electron transfer	Zero electron transfer
GaAs	15.00 meV	10.00 meV
$Ga_{0.8}Al_{0.2}As$	12.10 meV	08.40 meV
$Ga_{0.7}Al_{0.3}As$	11.50 meV	07.80 meV

For large barrier heights, the required transfer length is much longer than the coupler length and the transfer coefficient becomes negligible. As the barrier is reduced, transfer coefficient increases exponentially. At about 12.40 meV, complete electron transfer is achieved for $Ga_{0.8}Al_{0.2}As$ .If the barrier is further reduced, electrons are transferred back to the source waveguide and at about 08.40 meV, zero transfer is obtained. Similarly, transfer coefficient switches between 0 and 1 for GaAs and $Ga_{0.7}Al_{0.3}As$ at different values of barrier heights.

Conclusion

We have presented the switching characteristics of voltage controlled electron waveguide in which coherent tunneling results in electron transfer between two coupled electron waveguides. The most important advantage is that they offer the possibility to switch a current with a very low gate voltage. The resulting decrease in supply voltage may reduce power consumption.

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