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Demonstration of a reflective coupling diode in a coupled waveguide structure

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Despite the difficulty in fabrication, resonant tunneling diodes (RTD) have found a great deal of usage in the analog, digital, and mixed signal realms as a means of increasing the speed of signal processing circuitry or in reducing the static power dissipation in the circuitry. Nevertheless, RTDs suffer from their nonplanar structure. In this paper, we present a planar diode which operates via coupling of injected electron modes or a reflective coupling diode from an input waveguide to a corresponding output waveguide in a semiconductor hetrostructure. We demonstrate that the $I-V$ characteristics of this structure exhibit the characteristic negative differential conductance of RTD current–voltage characteristics. The resultant behavior of this planar device shows great promise for eventual implementation in ultrasmall high-speed circuitry.
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The resonant tunneling diode (RTD) has been a staple of physics for many years. It has found a great many uses in analog, digital, and mixed signal circuits.[1] However, the fact that the RTD must be fabricated using molecular beam epitaxy (MBE), which results in a nonplanar device, leads to some drawbacks. First the traditional RTD must be grown in layers with precise control over the application of different layers of atoms to form the device. If precise control of the location and thicknesses of atomic layers is lost, then the operation of the device could change significantly as the barriers change size and shape. These changes in the size and shape of the quantum well will accordingly alter the position and the form of the $I-V$ characteristics. While the science of MBE has reduced the probability of losing precise control of the atoms that impinge on a given substrate to form the RTD, this has not erased the problem of melding a nonplanar device into a planar integrated circuit. Therefore, efforts have been made to explore the possibility of using other quantum phenomenon to induce similar $I-V$ characteristics as those seen in the RTD.[2–6] In this paper, we present a planar-coupled waveguide device (RCD) which exhibits the characteristic $I-V$ plots associated with that of an RTD.

The structure under consideration is shown in Fig. 1. Two parallel waveguides, separated by an electrostatic potential barrier, are coupled via a tunnel region as in Ref. 7. The input (top) waveguide has a uniform width of 35 nm from start to finish, whereas the output (bottom) waveguide is narrowed at the source end with a width of 25 nm and then widens to a width of 45 nm after the coupling region in the middle of the structure. This wider output region assures that modes which propagate through the coupling region of length 335 nm and are not evanescent. The electrostatic potential barrier that separates the input and output waveguides begins with a width of 50 nm and then narrows to 25 nm after the coupling region. To achieve a more realistic potential profile for the barrier, the initial hardwall potential has been smoothed with a Gaussian distribution to provide a realistic depiction of the appearance of the depletion region around the metallic gates when they are biased. The potential barrier, however, is still sufficiently high to prevent any leakage from the input waveguide to the output waveguide and assures all transfer of density from the input to the output occurs in the coupling region.

With the structure defined, we now examine in Fig. 2 the variation of the transmission characteristics of an excited input mode as the Fermi energy of the structure is varied. Here we use a GaAs/AlGaAs heterojunction to demonstrate this principle. The Fermi energy in the structure is initially chosen to be 1.53 meV, which corresponds to a carrier density of $4.27\times10^{10}\,\mathrm{cm}^{-2}$. This Fermi energy corresponds to the smallest Fermi energy necessary to excite a propagating mode at the input of the structure. Since the input waveguide structure is wider than the output waveguide, the mode that is excited at this energy will only propagate in the wider input waveguide. The proportionate sizes of the respective input and output waveguides ensure that when the single input mode is excited, the resultant destination of the mode will be clearly determined. Further, the particular dimensions of the waveguide structure can be scaled easily as long as the constraints mentioned are honored. The simulation is performed on a discretized grid using a variation of the Usuki mode matching technique via the scattering matrix,[8] using a grid spacing of 5 nm. In Fig. 2(a), we see that, as the Fermi energy is varied, we pass through energies where the mode switches from transmitting the majority of its electron density from the input waveguide (T_{11}) to the output waveguide (T_{12}).[9] Nevertheless, as we progress in Fermi energy, we find that at around 1.65 meV we pass through a short range of energies that appear to be more reflective in both the individual and total transmissions than other surrounding energies, as seen in Fig. 2(b). We are now faced with two tasks: we wish to exploit this reflective behavior to produce nulls in the resulting current flowing in the device, which is calculated via the Landauer formula. We propagate the single

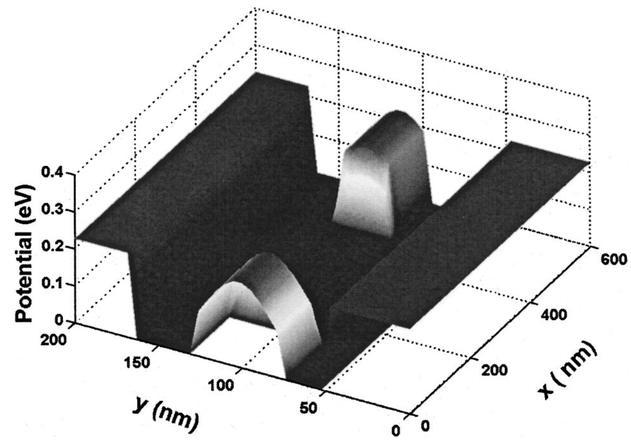

FIG. 1. Plot of potential profile of the structure under consideration. In this figure the coupling length between the two waveguides is 335 nm. The right-hand side of the structure ($x = 200$ nm) is defined to be the anode, while the cathode is defined to be the left-hand side of the structure ($x = 0$ nm).

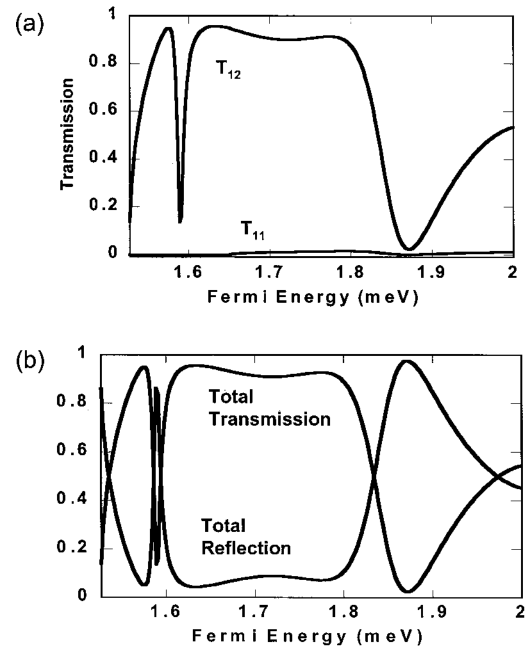

FIG. 3. (a) Plot of the individual transmissions (T_{11} and T_{12}) of a single incoming mode plotted against a varying Fermi energy with a local magnetic field of 4 T present in the output of the top waveguide. (b) Plot of the total transmission and reflection of a single incoming mode plotted against a varying Fermi energy with a local magnetic field of 4 T present in the output of the top waveguide. Notice that the total transmission is now equal to T_{12}.

mode present at the input of the device through a succession of slices with the energy of the mode changing from slice to slice in accordance with the changing Fermi level. The transmissions are then integrated for each bias point and the current is realized. Further, when we apply a bias to the device, we want to be able to measure the current in one of the output waveguides without needing to consider reflected electron density from the output of the device. To accomplish both of these tasks, we add a local magnetic field to the output of the top waveguide. This may be accomplished with a small biased wire over the two-dimensional (2D) electron gas. The local magnetic field changes the transmission significantly, as shown in the Fermi energy sweep of Fig. 3. In Fig. 3(a), we find that the addition of the local magnetic field at the output of the structure effectively blocks the output of the top waveguide, thus forcing the transmission to zero. Further, in Fig. 3(b), we find that we now have a large amount of reflection around 1.6 meV and again at about 1.87 meV. In this latter plot, we see that the total transmission is simply equal to T_{12}.

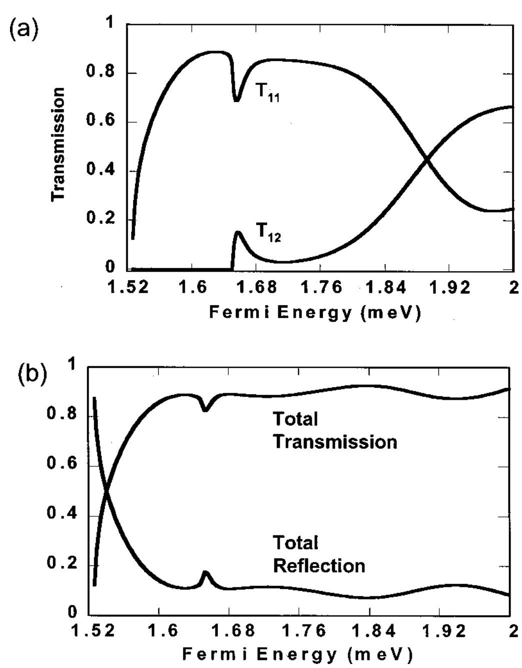

FIG. 2. (a) Plot of the individual transmissions (T_{11} and T_{12}) of a single incoming mode plotted against a varying Fermi energy. (b) Plot of the total transmission and reflection of a single incident mode plotted against the Fermi energy.

The high reflection values of energy can be explained by the fact that, at certain energies, the velocity of the incoming mode leads to a resonant length commensurate with the length of the tunneling region. When this happens, the mode will couple from the input waveguide to the output waveguide. We produce more pronounced nulls in Fig. 3 when the velocity of the incoming mode is such that it will maximize T_{11}. The addition of the local magnetic field forces more pronounced nulls due to the fact that, when the velocity of the mode is commensurate with a T_{11} maximum, the mode is almost totally reflected. It is important to note that we have not optimized the material used when the local magnetic field is included in the system. Since the magnetic field used to form the barrier in the output of the top waveguide is normally rather high, on the order of 4 T, we may not actually get the barrier effect we desire. The large magnetic field may cause spin-dependent transmission of electron density in the top waveguide through the Zeeman effect. We may neglect this effect in our case due to the low g factor of GaAs (-0.44). However, in other systems such as InAs which has a g factor of -15, the Zeeman splitting may no longer be neglected, and we will have spin-dependent transfer of electron density in the top waveguide. This polarized

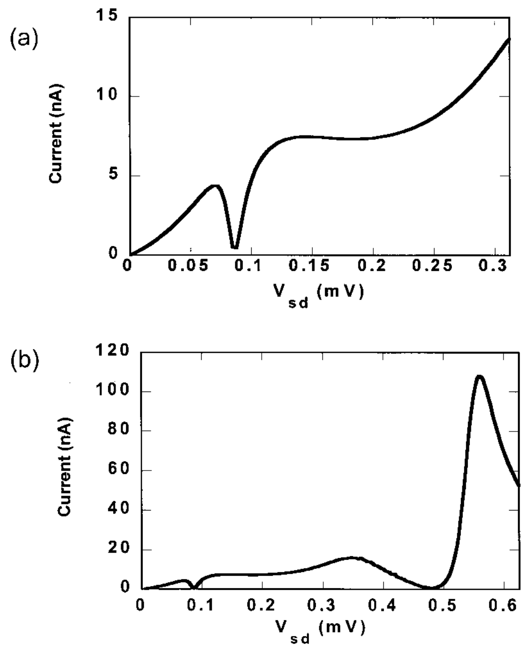

FIG. 4. (a) Plot of the total current in the device plotted against the applied source-drain bias. (b) Plot of the total current in the device plotted against an extended range of applied source-drain bias.

transmission of density will affect the resultant $I-V$ characteristics and could have an adverse effect on the operation of the device.

With the behavior of the transmission of a single mode understood under conditions of varying Fermi energy, we now exploit this described behavior in the following fashion. We set the Fermi energy to be 1.53 meV, which, as stated previously, corresponds to the minimum Fermi energy required to excite one propagating mode in the input of the top waveguide. We now apply a positive bias to the system. The application of the positive bias to the system will then spatially modulate the Fermi energy of the system and, therefore, the velocity of the propagating mode. The results of this simulation are shown in Fig. 4. As we see in Fig. 4(a), the resulting current is modulated by the positive applied bias. Since a range of energies propagate to the drain, a subsequent convolution of the various transmissions will take place over the highly reflective energies seen in Fig. 3. This results in the valley of the $I-V$ curve seen in Fig. 4(a) at an applied bias of 0.1 mV. Moreover, the combination of reflected and transmitted electron density required to form the peaks and nulls in the output current is repetitive, as seen in Fig. 4(b). As the applied bias is increased, the corresponding velocity of the mode will again be swept through a highly reflective state where the natural tendency of the mode will be to transmit to the top waveguide. This behavior is seen in Fig. 4(b) where, as the applied bias is increased, we modulate the velocity of the mode through another highly reflective state producing another null in the current just before 0.5 mV.

In conclusion, the reflective coupling diode seems to present a viable planar option for future circuit design. We have demonstrated that, through the properties of the coupled waveguide system, we may apply a bias and sweep the velocity of an incoming mode through highly reflective states in the system producing RTD-like $I-V$ characteristics.

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