Magnetically and electrically tunable semiconductor quantum waveguide inverter

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In recent years, quantum computing and information theory has received a great deal of attention as a means of drastically improving the computational speed and resources traditionally associated with current binary implementations. We present an electrically tunable semiconductor quantum waveguide implementation of an inverter gate in a GaAs/AlGaAs heterostructure in which the output of the waveguide structure may be selected via the application of an appropriate magnetic field or electrical bias. The resulting behavior observed by our implementation shows a great deal of promise for an eventual semiconductor realization of this basic qubit structure. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1525073]

In recent years, quantum computing has received a great deal of attention as a possible means of achieving very rapid computation speeds as compared with that of the classical computation.[1,2] However, in addition to simply being a method to speed the computation, quantum computing offers tremendous promise in areas that are currently unrealizable, such as quantum teleportation[3] and the factorization of large prime numbers.[4] Quantum computation theory has been structured around the use of a qubit, or quantum bit. Two or more bits of quantum information are coupled together to achieve basic logic structures whereby the most basic and essential coupling of two qubits is the controlled not gate (CNOT). One popular realization of this gate is in the Fredkin gate.[5] The Fredkin gate consists of a control bit, coupled to a qubit, and it operates on the following principle: if a "1" is present in the control bit, then the qubit is passed unchanged. On the other hand, if a "0" is present in the control bit, then the qubit is inverted. In a recent study, a semiconductor implementation of an inverter structure has been introduced in which quantum waveguides are arranged in a parallel fashion with a small coupling region placed between the two waveguides.[6] In this letter, we build on the structure in Ref. 6 and present a coupled waveguide structure which is capable of controlled transfer of density to either waveguide through the use of either a magnetic field, or the application of an electrical bias across the device in an effort to implement the CNOT structure in a semiconductor hetrostructure without the use of localized states, as with a Gaussian wave packet.[7]

The structure studied here is shown in Fig. 1. Two parallel waveguides, separated by an electrostatic potential barrier, are coupled via a tunnel region. 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 propagate through the coupling region and do not decay. 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. 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. The Fermi energy in the structure is chosen to be 2 meV which corresponds to a carrier density of 5.6×10^{10} cm^{-2}. This Fermi energy is chosen so that only one mode is excited in the input waveguide of the structure. This 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.

The density in the structure for varying coupling lengths is calculated to find the maximum output. The results of this simulation are shown in Fig. 2. In Fig. 2(a), we see that there are periodic fluctuations in transmission from the input waveguide to the output of the second waveguide (T12), and

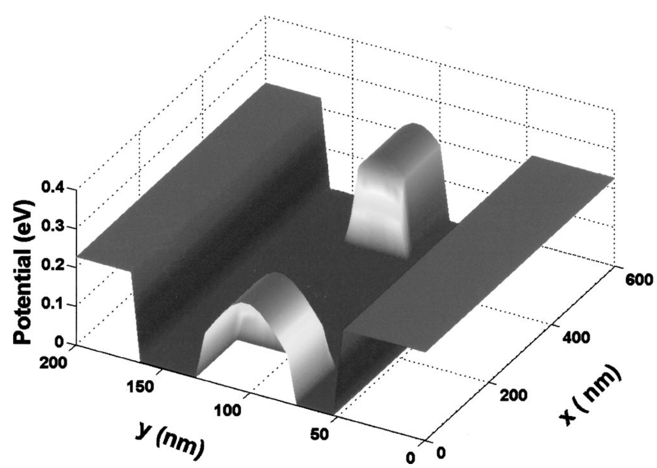

FIG. 1. Plot of the coupled waveguide structure under consideration. In this figure, the coupling length between the two waveguides is 335 nm. The right-hand side of the structure ($x = 200$ nm) is defined to be the anode while the cathode is defined to be the left-hand side of the structure ($x = 0$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

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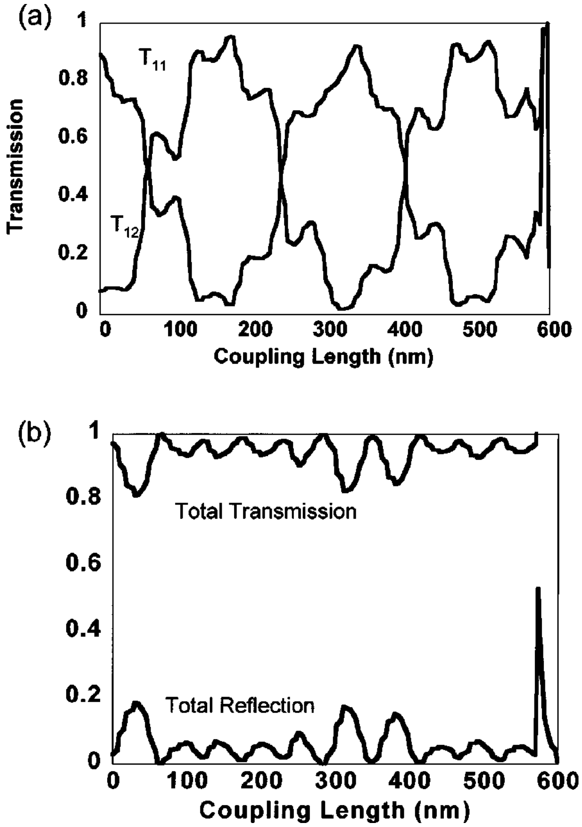

FIG. 2. (a) The individual transmissions (T11 and T12) plotted over the coupling length between the two waveguides. (b) Total transmission and reflection plotted over the coupling length between the two waveguides.

from the input waveguide to the output of the initial waveguide (T11). These fluctuations are periodic in coupling length at approximately 300 nm. Clearly, we can see that every 150 nm we find ourselves in an almost ''pure'' state ($|0\rangle$ or $|1\rangle$). For other coupling lengths, we find ourselves at intermediate locations on the Bloch sphere and thus find superposition states. In Fig. 2(b), we plot the total transmission and total reflection against the coupling length. We see that there remains a reflected component of 0.0671 at the optimum coupling length which accounts for the remainder of the density.

In Fig. 3(a), we plot the density with no magnetic field and observe, as before, that the majority of the density remains in the input waveguide cathode maximizing T11. As we can see in Fig. 3(b), with a magnetic field of 0.705 T, the wave function is transferred from the input waveguide anode to the output waveguide cathode via the coupling region and a pure inverted state in the system is achieved by maximizing T12. From Fig. 3(c), T12 is approximately 0.983, T11 is approximately 3.451×10^{-5}, and the total reflection is approximately 0.0171. While T11 is greater than zero, the value of this transmission is negligible compared to T12, which can be regarded as a pure state. Furthermore, from Fig. 3(d), we see that the application of a magnetic field is a symmetric process in total transmission and reflection, but is not for the individual transmissions of the input and output waveguides (T11 and T12) individually. Minima of transmission occur at half-integer multiples of the cyclotron radii compared to the corresponding coupling length of the structure. Based on these results, we conclude that, using this coupled waveguide structure a small magnetic field of 0.705 T will switch the output from a ''low'' to a ''high'' or ''high'' to ''low'' state.

While it is clear that the output of the coupled waveguide structure may be switched using a magnetic field, it is not clear that the application of a magnetic field is the most efficient way to switch a qubit. While the application of a magnetic field through the use of a small wire may be acceptable in the case of a single qubit, magnetic switching is not feasible in the case of a multiple qubit structure. With the qubit structures packed very tightly in the semiconductor structure, we would then, conceivably, need many wires to switch the various individual qubits. When the wires are brought into close proximity to each other, the magnetic fields of the individual wires would interfere and the result would be a shift in the magnitude of the magnetic field that the qubits would see. This can be seen in Fig. 3(c), where the

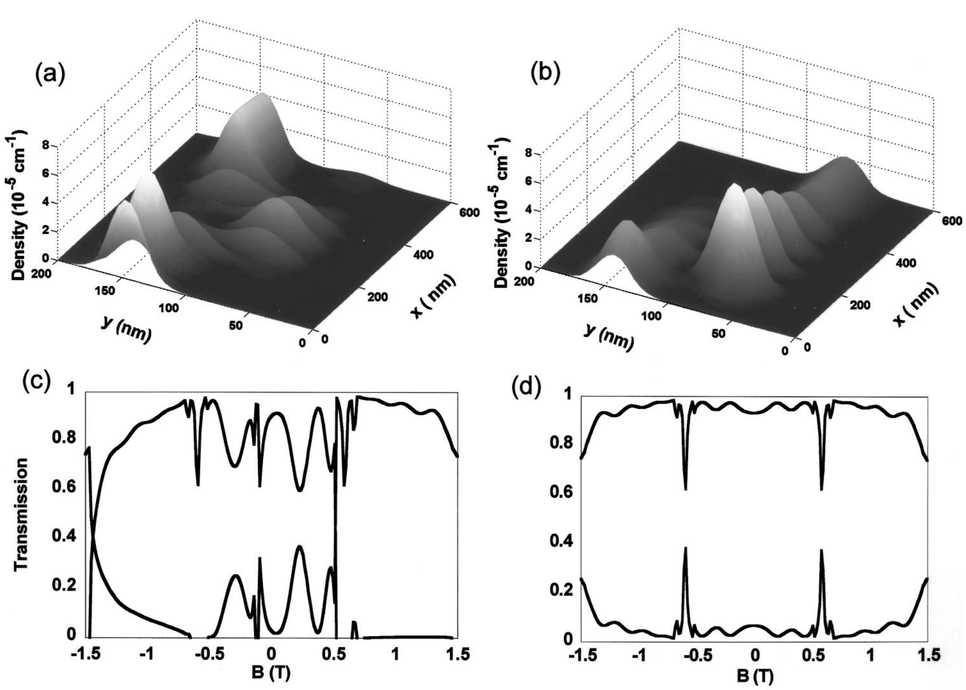

FIG. 3. (a) Density at zero-magnetic field with the coupling length set to 335 nm. (b) Density with a 0.705 T magnetic field applied to the structure. (c) T12 and T11 plotted over a varying magnetic field. (d) The total transmission and reflection plotted over a varying magnetic field.

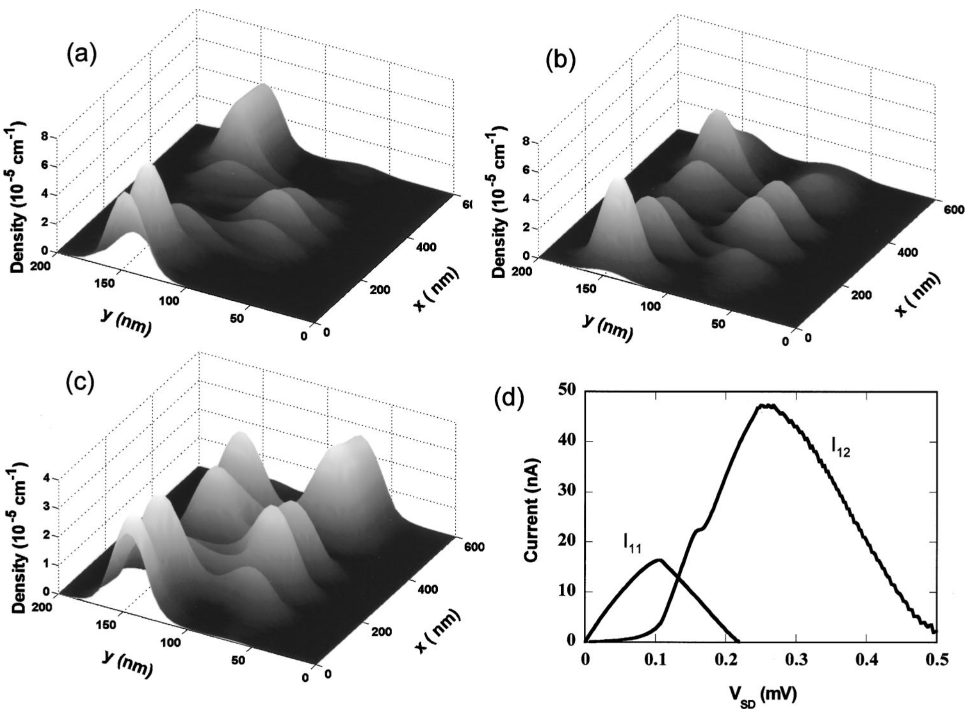

FIG. 4. (a) Density with zero applied bias at 335 nm. (b) Density with −0.243 mV applied bias. (c) Density with −0.318 mV applied bias. (d) Individual currents (I11 and I12) plotted against a varying applied bias of 0→ −0.5 mV.

plateau is not terribly stable as small changes in the magnitude of the magnetic field would produce a superposition state. Therefore, it is preferable to seek a means by which the state of the qubit may be changed through the application of an applied bias. This case is considered to be more ideal as the bias may be applied in a much more localized fashion than the magnetic field.

In Fig. 4, we plot the results of adding a voltage drop, ranging from 0 to −0.50 mV, across the coupled waveguide structure with the anode at the right-hand side and the cathode at the left-hand side of the structure. This adds an extra degree of freedom to the carriers in the system, and it is no longer viable to discuss the operation of the device in terms of just the transmissions and reflections of incident modes. The addition of an extra degree of freedom to the carriers excites extra output modes which are indistinguishable in the total transmission from the initially excited mode (determined by the setting of the Fermi energy). Therefore, in order to determine the extent to which our device switches from one pure state to the next, we use the Landauer formula to integrate over the individual transmissions and compute the current. In Fig. 4(a), we show the density plotted with no applied bias at the T11 maximum. We now apply a negative bias (applied uniformly from the source at the left-hand side end to the drain at the right-hand side end) across the device and show the density resulting density change in Figs. 4(b) and 4(c) for applied biases of −0.243 mV and −0.318 mV, respectively. While it is clear from Figs. 4(b) and 4(c) that the majority of the density has switched and is now propagating at the output waveguide cathode, we must look to the current flowing in each waveguide to determine the level of our success in switching of the waveguide states. In Fig. 4(d), we see that in the case of both the −0.243 mV and −0.318 mV applied biases, we have no current flowing in the input waveguide cathode (I11) and a vast majority of the current flowing in the output waveguide cathode (I12), thereby giving us a switched state. We note that the magnitudes of the currents flowing at these applied biases are 46 nA at −0.243 mV applied bias and 40 nA at −0.318 mV. Further, we find that in both cases the total current, and the current that is flowing at the anode end of the output waveguide, are equal. Thus, the switching from one pure state to another is complete as the applied bias is increased. Moreover, we find that the current in the device pinches off at −0.6 mV. This is expected, as when the applied negative bias increases, the Fermi level at the anode end of the structure eventually drops below a point in energy where propagating modes can be supported in the structure. Therefore, the device pinches off.

In conclusion, the coupled waveguide inverter system presented is a viable candidate for future quantum computing applications. We have shown that this structure has the capability of being switched from one pure state to another either through the use of an applied magnetic field or an applied bias.

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