Initial State Preparation and Stability in Narrow Band-Gap Semiconductor Qubits

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ABSTRACT

Solid state quantum computing has been an area of intense research over the past few years. In most semiconductor implementations, III-V materials have been used in order to exploit their comparatively long mean-free paths and phase coherent times. While most of the attention has been focused on the different possible implementations of gates necessary for computation, little effort has been made to examine the preparation and stability of the initial state of these semiconductor qubits. In this paper, we examine initial state preparation and stability in coupled waveguide qubits formed in several III-V semiconductor hetrostructures. We examine the sensitivity of the initial state to variations in the coupling length between the waveguides, material disorder introduced through mean-free path approximations, and through introduction of phase coherent times.

Keywords: quantum computing, qubit, stability, initial state, nanostructures.

1. INTRODUCTION

The output of a quantum computing system depends on the quality of the preparation of the initial state of the qubit or qubits to be used in the subsequent computations. Here, we define a qubit structure using a coupled waveguide system, as shown in Fig. 1. To prepare the initial state of the qubit, we set the coupling distance between the two waveguides to a point which corresponds to the desired electron density transfer between the input portion of the qubit and the output portion of the qubit [1]. To this end, it is advantageous to use narrow band-gap semiconductor materials for quantum computing applications due to their relatively long phase coherent times and high mobilites. However, while favorable parameters are attainable in narrow band-gap semiconductors, it is valid to question the stability of the initial state under disorder, which may arise through either mean-free path variations or phase coherent length variations, or through an imprecise definition of the coupling region. We treat InAs, GaAs, and InSb.

The simulation of these effects is performed on a discretized grid using a variation of the Usuki mode matching technique via the scattering matrix [2], using a grid spacing of 3 nm.

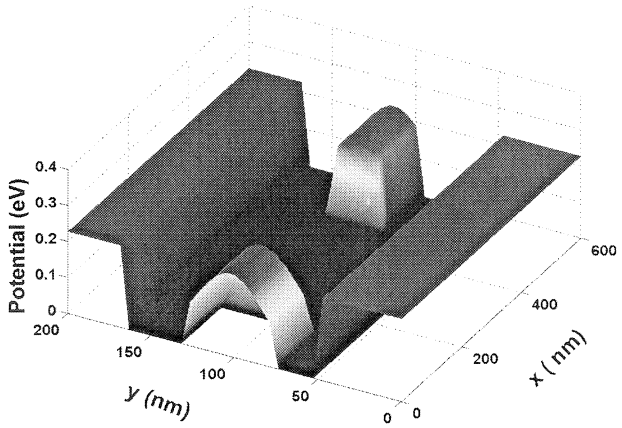

Figure 1: Potential profile for the coupled waveguide qubit. Above the coupling length has been set to 330 nm.

2. QUBIT STRUCTURE DESIGN

The qubit, shown in Fig. 1, consists of two parallel waveguides, separated by an electrostatic potential barrier. The two waveguides 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 50nm and then narrows to 25nm 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.

While the design of the qubit is the same for each of the hetrostructures, the Fermi energies differ for each of the materials. The Fermi energy in the GaAs structure is chosen to be 2 meV which corresponds to a carrier density

of 5.6×10^{10} cm^{-2}, in InAs the Fermi energy is chosen to be 9 meV which corresponds to a carrier density of 9×10^{10} cm^{-2}, and in InSb the Fermi energy is chosen to be 19.5 meV which corresponds to a carrier density of 1.11×10^{11} cm^{-2}. These Fermi energies are chosen so that only one mode is excited in the input waveguide of each qubit. 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.

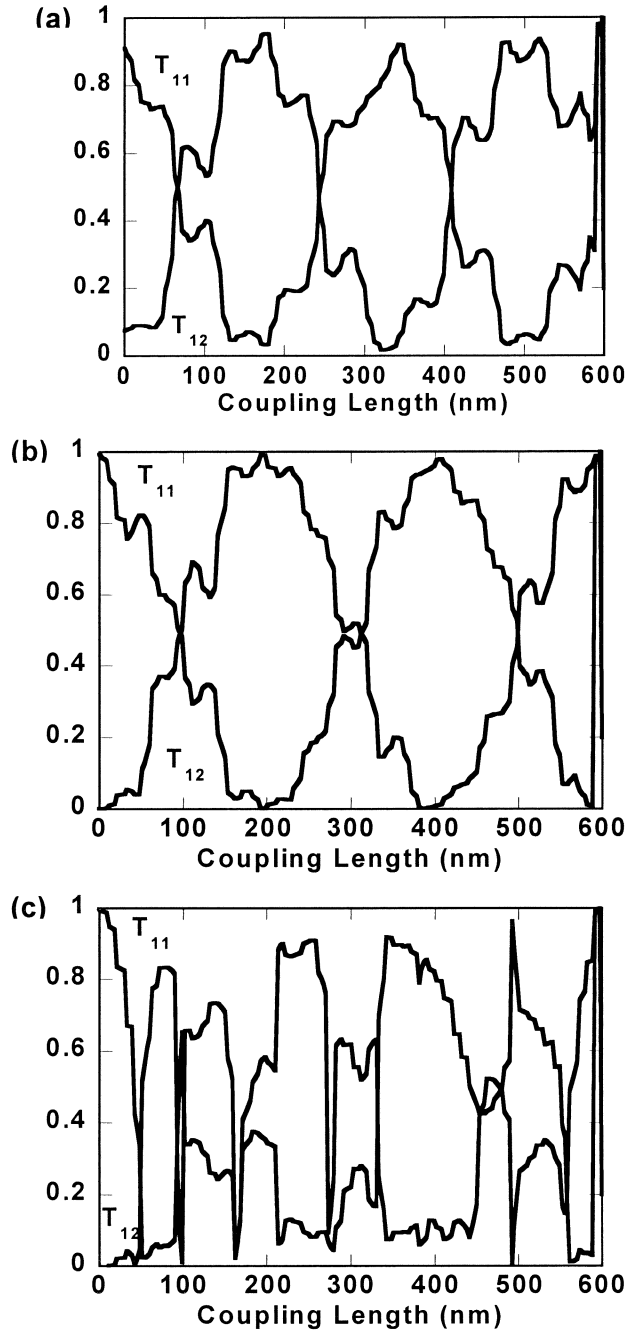

Figure 2: Qubit state plotted against coupling length for (a) GaAs (b) InAs (c) InSb.

3. IMPRECISE COUPLING LENGTH DEFINITION

In Fig. 2, we see the initial state of the qubit plotted against the coupling length variation for GaAs, InAs, and InSb. We find that, in InAs and GaAs, there is a very periodic pattern in the density transfer at each respective Fermi energy. For InAs, the period appears to be approximately 400 nm whereby we recover the superposition of the states at every 200 nm. For GaAs, we find a period of approximately 300 nm with pure states occurring in intervals of 150 nm. Finally, for InSb, we find a period of 150 nm with pure states occurring at every 75 nm. Clearly, as illustrated in Fig. 2, we may prepare any range of initial states in the qubit simply by setting a coupling length. Nevertheless, while it is possible to set the initial state of the qubit, we see that it is only the pure states that have any stability in the semiconductors studied. All of the superposition states must be very precisely defined. Any variation of the coupling length, while preparing a superposition state, would result in a different superposition state. This arises from the fact that, since we hold the velocity of the impinging mode constant, changes to the length of the coupling region will change the coupling condition, thereby changing the mode transmission conditions [2]. Moreover, we see that, in InSb, the pure states are not even stable. At certain maxima, a change in coupling length of approximately 30 nm returns the qubit to a superposition state, which as we can see is very unstable.

4. DISORDERED MATERIAL EFFECTS

Thus far, we have shown that the definition of the coupling length is very important, not only in the preparation of the initial state of the qubit, but also in the overall stability of the state. Nevertheless, we have neglected to this point the fact that, in an actual semiconductor hetrostructure, there are impurities present. To examine the effects of inelastic scattering on the stability of the qubits, we add a uniformly distributed random perturbation of energy width W to the on-site energy $E(i,j)$, which corresponds to a distribution of scatterers having a delta function potential, or:

$$\frac{W}{E_F} = \sqrt{\frac{6\lambda_F^{\,3}}{\pi^3 a^2 \Gamma}} \quad . \tag{1}$$

Here, λ_F is the Fermi wavelength, a is the grid spacing and Γ is the mean-free path [3]. When this is included in the simulation, the stability of the qubits may be once again examined for a varying coupling length with a concentration of scatterers corresponding to a mean-free path of 1 μm. This is shown in Fig. 3.

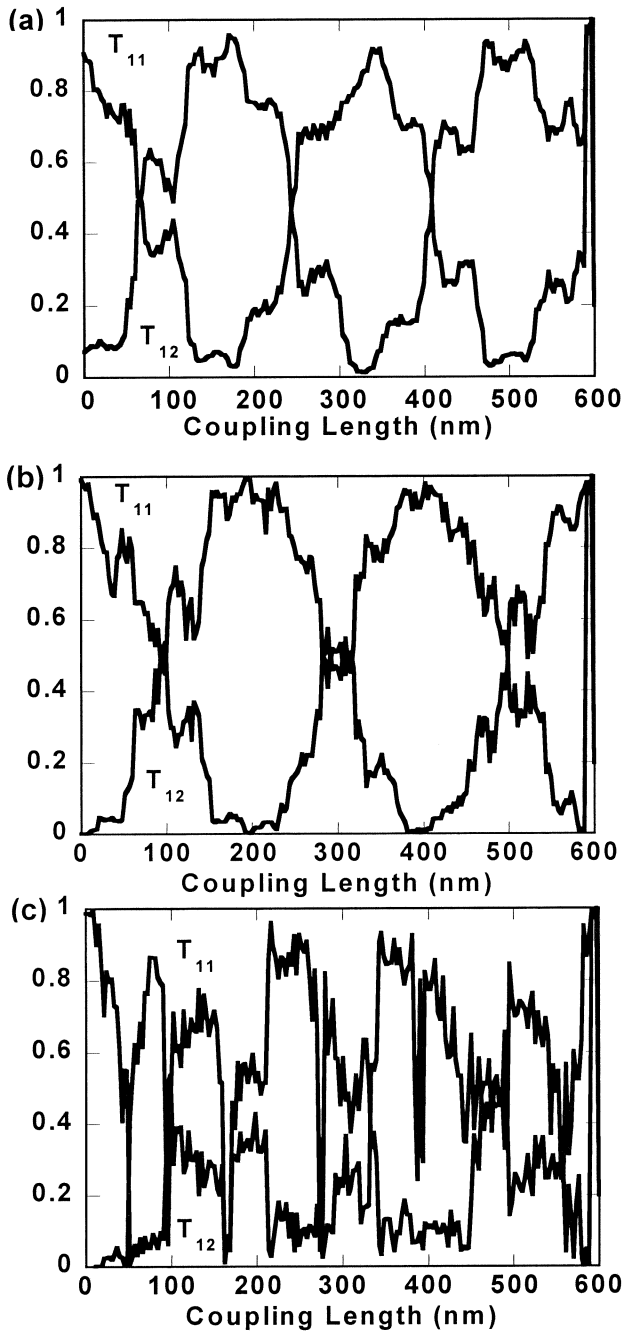

Figure 2: Qubit state versus coupling length for (a) GaAs (b) InAs (c) InSb with a mean-free path of $1\mu m$.

We see that the addition of scattering causes moderate instabilities in both GaAs and InAs, as shown in Figs. 3(a) and 3(b). These instabilities shrink the region of stable maxima in both materials for a moderate, experimentally verified mean-free path. While we still have relatively stable, and periodic, maxima and minima, the main effect is most pronounced in the superposition states. In the superposition states, we lose any predictability that we once had with the pure material case, as any variation in the coupling length has a pronounced effect on the state of the qubit. However, the scattering only induces moderate variations in InAs and GaAs pure states, but the effect is severe in InSb. In Fig. 3(c), we see that the addition of moderate disorder in the InSb qubit causes total instability.

Fig. 3 shows that the introduction of a moderate amount of disorder into the system further destabilizes the superposition states of the qubit in each of the semiconductors studied. Nonetheless, if we increase the amount of disorder in the system by decreasing the mean-free path to 0.1 μm, we see in Fig. 4 that this is enough to destabilize even the pure states in GaAs.

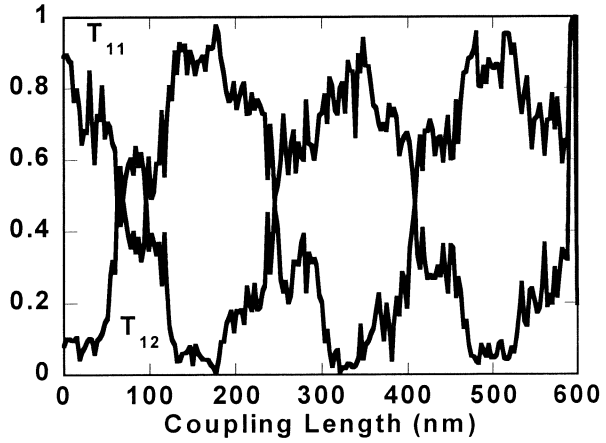

Figure 4: GaAs qubit state versus coupling length with a mean-free path of $0.1\mu m$.

5. PHASE DECOHERENT EFFECTS

To examine the effects that phase coherency has on the stability of the semiconductor qubit, we include phase randomization in the simulation by introducing an imaginary potential [4]. For a phase coherent time τ_ϕ, the original site energy becomes:

$$V_{\mathrm{mod}}(i,j) = V_{site}(i,j) - iV_{ph}(i,j) \ , \tag{2}$$

where

$$V_{ph} = \frac{\hbar}{2\tau_\varphi} \ . \tag{3}$$

We examine this effect with a phase coherent time of 0.5 ns. The effect this has on the stability of the qubit in shown in Fig. 5. From this figure, we see that there is no significant change from the original case where we did not consider the phase coherent time. As the phase coherent time continues to decrease, we will see a degradation of the stability of the qubit state. This will be due to the fact that ,

with shorter phase coherence times, an increasingly large complex part of the potential appears in the site energy. This will force lower values of the transmission at all coupling lengths. At the quoted Fermi energies, the transmissions eventually decay to zero as the phase coherent time decreases, but this effect may be countered by propagating at higher Fermi energies.

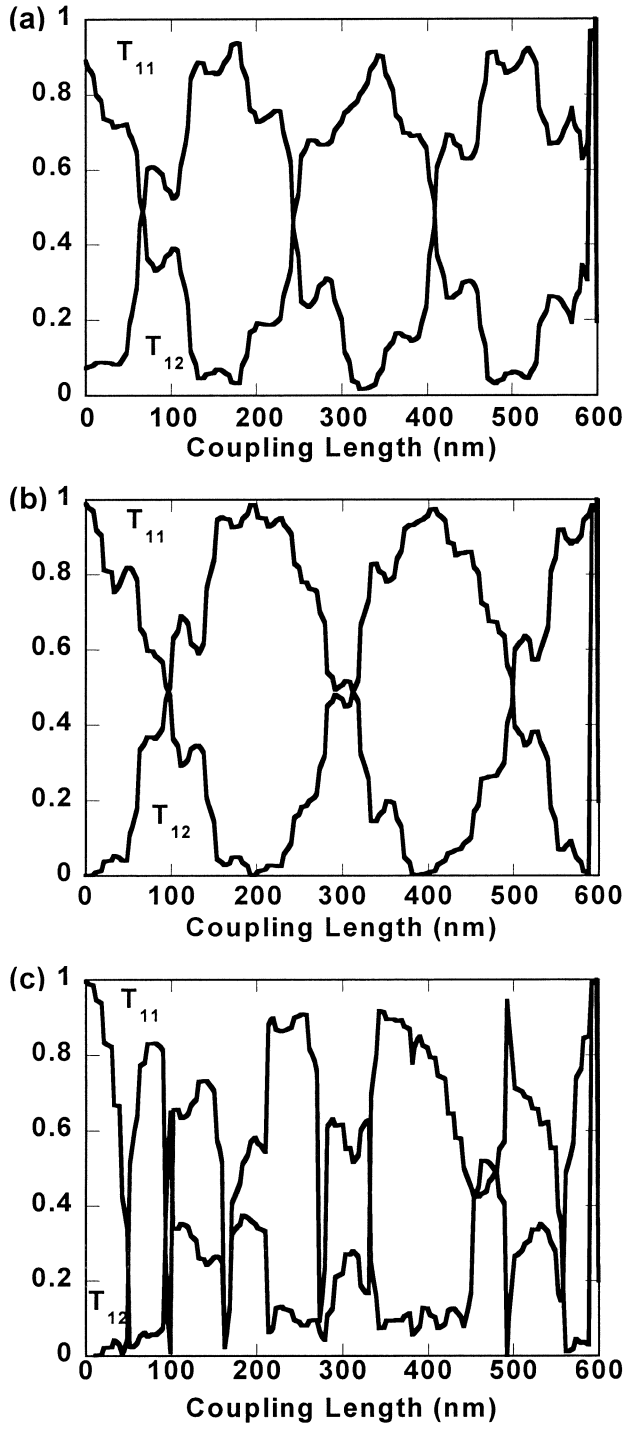

Figure 5: Qubit state versus coupling length for (a) GaAs (b) InAs (c) InSb with a phase coherent time of 0.5 ns.

6. CONCLUSION

We have demonstrated that coupled waveguide qubits in both GaAs and InAs show strong promise for future quantum computing applications. These materials show stable, periodic oscillations and pure states may be easily selected. Further, these pure states remain stable under moderate amounts of inelastic scattering and phase coherence times. However, great care must be taken to prepare superposition states, as these states are quite vulnerable to variations in both the coupling length and scatterer concentration. Further, we have shown that InSb is not a good candidate for quantum computation, as states prepared in this compound appear to be unstable under both coupling length variations and scatterer concentrations.

ACKNOWLEDGEMENTS

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