FABRICATING ALL-OPTICAL LOGIC GATES WITH THE AID OF DOUBLE QUANTUM WELLS

MAEDEH BAHRAMI

ABSTRACT

In the present article, a very high speed all-optical digital processing method, particularly for NAND gates has been suggested, which has been stated based on the energy transmission in the Intersubband (Interband) and in the semiconducting quantum wells. Our purpose for focusing on NAND gates is that they are used in most logic circuits and are considered as the base gate in fabricating and designing other combinatory gates and logic circuits. In this article, for designing the NAND all-optical gate, double quantum well with an InGaAs-AlAsSb structure was used. The results of conducted experiments and studies showed that using a double quantum well with an InGaAs-AlAsSb structure also provides the possibility of operating on Telecom wavelengths. In addition to this, using this structure does not have the problems that other fabricated optical gates have, such as low-speed operation, low working frequency range and linear performance in a limited range.

KEYWORDS : Energy levels, Quantum wells, Optical signal processing, Telecom wavelengths, Logic gates

Signal processing by using high speed optical instruments in a time arena, has many significant advantages that one of its most important advantages is reducing a large amount of traffic in 10^{12} bit optical networks [Hamilton and Robinson, 2011]. For digitally preparing a processor signal, we need a complete set of logic operators, which NAND operator is also one of those and in fact is among the base operators that with its help, other operators are fabricated and designed. Moreover, running the monitoring as for error detection is also possible through the NAND gates. For this reason, in this article we have also focused on the fabrication and designing of NAND all-optical gates. Nowadays, optical logic gates are used in many applications including fiber optics [Islam, 2003] or semi-conducting optical amplifiers (SOA) [Sharaiha et al., 2007]. However, despite the relative success of the designed systems, there are some issues, including lengthy latency period in silica dioxide fibers and low-speed operation due to lengthy transitional period in SOAs. For this reason and following other researchers’ studies for reducing the disadvantages of the previously fabricated optical gates, in this article, we use the energy transmission technique in a double quantum well with an InGaAs-AlAsSb structure for designing optical logic gates.

Quantum Wells Theorem

About two thirds of the research conducted in the field of semiconductors’ physics, have been done in regards to semiconducting multi-structures, and particularly binary multi-structures that include quantum wells, quantum wires and quantum dots. Scientists’ exceptional interest in this branch of Physics is because of its extraordinary applications and its undeniable impact on the advancement of human life. Semiconducting multi-structures have provided the possibility to resolve essential problems in semiconductors and through it, controlling many of fundamental parameters of crystal semiconductors have been made possible. These parameters include energy gap, particle’s effective mass, carriers’ mobility, refractive index, band structure and etc., which by adjusting them, not many problems are left in controlling the particles in structures and for achieving desirable results. The invincible control over essential parameters in these structures has created components with higher productivity that can be discussed as in the following examples: all types of binary multi-structure lasers that are used for compact discs (disc players) and in complex telecom systems. Transistors with low noise and high electron mobility that are used in components with a strong frequency application such as, satellite televisions, multi-structure solar cells used in space and etc. One of the multi-structures’ subtypes is the quantum multi-structures. If particles’ confinement was solely taken place in one dimension, this structure is referred to as a “quantum well”. In these structures effects are observed that are due to the low and comparable bandwidth of layers with De Broglie wavelength and are referred to as “quantum-size effects”.

Solids’ Band Structure

In order to understand the concept of energy bands, first we must consider the isolated atoms and then we put them next to each other so they constitute a solid’s molecule. If the detachment between atoms is infinite, atoms are independent, and therefore, have atomic energy levels; however, when we draw the atoms closer to each other, the electrons become affected by the adjacent core and neighboring electrons. Gradually, when atoms come closer to each other, electrons have more effects on each other and when this closeness of atoms leads to molecule formation, every atomic level is split into multiple molecule levels, which this phenomenon is called “level widening”. These continuous energy levels have specific energy bandwidth and are called “energy bands”. Generally, every energy band is separated from its neighboring energy band through a forbidden band gap. If the two atoms come close to each other, an interaction occurs between them and the functions of electron waves have interactions among each other, which this matter eliminates degeneration, in
This case, each of the levels (figure 1-A) as shown in figure 1-B are turned into a binary level; as atoms come closer to each other, the interaction potential becomes stronger and the levels’ splitting will be stronger. The interesting point here is that the splitting of electron levels that are closer to the core is less than those levels that are farther; this matter is due to the fact that electron carriers in closer levels are bound to the core and this constraint is much stronger than the effect of atoms’ looseness and therefore the interaction potential of them is less when compared to those levels that are farther from the core. A set of these sublevels can be considered as energy bands.

**Figure 1: Splitting of energy levels in the combination of two atoms**

**Classification of Solids**
Electrons' filling in levels occurs according to Pauli’s Thread principle. Imagine a crystal in a base state and when no stimulus is applied (low temperature), under such conditions, when electrons are completely fitted into the levels, the highest energy band that is completely full, is called the “tolerance band” and the band after, that has more energy and might be empty or half-full, is called the “conductivity band”. Based on the above-mentioned descriptions, the classifications of solids will be as the following: if the conductivity band was part full and part empty, the crystal is a metal; if the conductivity band was empty then it is an insulator. Metals are good electrical conductors, because when we stimulate electrons through the electrical field or other factors, they easily move from the occupied states of the conductivity band to the unoccupied states of the same band, such transitions are called “Interband transitions”. In nonconductors the energy difference between the tolerance band and conductivity band is very much and stimulation factors are usually unable to supply the interband transition energies, also because the tolerance band is full, interband transitions are not possible. In the event that the energy gap between the tolerance and conductivity bands is about 1 ev, the crystal will be a semiconductor, which they make the stimulation for interband transitions possible.

**Quantum Wells**
If we limit the degrees of freedom for the carriers’ movement, trapped quantum structures are created. The reason these structures are called “quantum structures” is that the movement limitation in distance about few tens of angstroms leads to the emergence of quantum characteristics for carriers. In the case where trapping happens in one dimension and the particle has a continuous spectrum of energy in two dimensions and one dimension moves on discrete levels, this structure is called a “quantum structure”. If we perform the trapping in two dimensions, it is called a “quantum wire” and if is done in three dimensions is called a “quantum well”. For making a quantum well we need two substances with different band gaps; if the substance with a smaller band gap is sandwiched between the substances with larger band gaps, the substance with a smaller band gap is called the “well” and the substance with a larger band gap is called the “barrier”. Particles that are in the structure are inclined towards the natural form so that they are placed in a position where they are more sustainable and have a lower level of energy, thus, they are placed in the well. Band detachments in other words the energy difference between the barrier and well in the conductivity band, and also, band separation in the tolerance band is the energy difference between the barrier and well in the tolerance band. Figure 2 is a singular quantum well. If we place several of these next to each other, we will have a multiplex quantum well structure.

**Figure 2: AlGaAs semiconducting quantum well structure**

**FABRICATING AN ALL-OPTICAL NAND GATE USING QUANTUM WELLS’ CHARACTERISTICS**

**Energy Transmissions in Interband and Intersubband for Optical Logic Operators**
Intersubband transmission in semiconducting quantum wells that occurs in the conductivity bandwidth, is an executable mechanism for an all-optical logic. This mechanism has several interesting features such as very small resting time, bipolar torque of large transmission and extensive range of transmission wavelengths that are adjustable [Rosencher et al; 2000]. It has also been discovered that ISB-T can simultaneously be used with the transmission in Interband [Noda et al; 2005]. For example, when the electrons created with type n doping in a lower conductance subband stimulate a higher subband through ISB-T light resonant, temporarily, the electron’s density reduces and therefore the IB absorption increases. Consequently, the IB-T light resonant can be modulated with the ISB-T light resonant. Figure 3 shows a
schematic of the modulation of IB-T light resonant through ISB-T optical resonant.

Figure 3: Schematic of the Modulation of IB-T light resonant through ISB-T light resonant

A NAND optical gate becomes possible by presenting an input signal to the ISB-T light resonant in a coordinated time with IB-T light resonant's radiation. The output signal is modulated through the IB-T light resonant. When an input signal is stimulated the IB-T light resonant is absorbed and therefore the output signal does not enter the input. When there is no ISB-T light resonant, the device becomes a passageway for IB-T light resonant and thus, the output signal is at a high degree. Therefore, the truth table for NAND is completed.

Table 1: NAND Gate Truth Table

<table>
<thead>
<tr>
<th>INPUT A</th>
<th>INPUT B</th>
<th>OUTPUT (NAND)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISB-T</td>
<td>IB-T</td>
<td>IB-T</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
<td>1</td>
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<td>1</td>
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<td>0</td>
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In addition to this, the NAND operator can also become operational through the simple framework that is shown in figure 4. In this device the two input signals of A, B non-uniformly cross each other and then act as the ISB-T light resonant for the device. Also, the IB-T light resonant has radiated at the same time.

Figure 4: Block diagram of the designed NAND operator

If the pulse energy for input A, B is zero or $E_{in}$, the radiation energy to the device can be zero or $E_{in}^\frac{2}{2}$. The output signal that is modulated through ISB-T light resonant must be at a lower degree when the radiated optical energy is $E_{in}^\frac{2}{2}$, then a NAND gate is obtained. These operations are successful when the amount of signal is selected at an appropriate level; when ISB-T causes saturated absorption, the number of inputs might be more than 2 inputs. Therefore, it is observed that only when all inputs are one, the device output is one. This NAND behavior can be applied for manifesting a specific component of the separated channel N, as in finding a solid buffer from amongst the empty or half-full channel N and etc..

Experiment, Design and Calculations using Double Quantum Wells with an InGaAs-AlAsSb structure

An important matter that should be considered in this article is operating in telecom wavelengths of 1.3 $\mu m$ and 1.5 $\mu m$ that has been made possible in CDQ-Ws with an InGaAs-AlAsSb structure and can also be observed in figure 5a. Where ISB-T occurs at 1.5 $\mu m$ wavelength and IB-T occurs at 1.3 $\mu m$ wavelength, waveguide at 3.5mm wavelength with polished sides of 45° that an active layer was combined with it was used in this experiment. The device is used in a multilateral reflection state with a 45° angle (figure 5b).

An optical parameter amplifier is pumped through a productive open amplifier that this operation is conducted for producing ISB-T resonant pulses at 150-fs. IB-T resonant pulses include wavelengths with ranges of 1.1 to 1.3$\mu m$. The
change in the absorption level of IB resulted through ISB-T light resonant is a set of wavelengths at ranges of 1.28 to 1.32 μm that has caused a very fast decay time at 880-fs speed. The transmission of IB-T light resonant that is shown in figure 6a is as an energy density function of ISB-T resonant pulses. When the device is exposed to two absorption photons, the absorption level at inputs with higher energesis further increased. For NAND logic the transmission must be equally low at the output stage for the E in 2 input energy so that constant zero is produced. Also for ISB-T radiation energy, the E in must be so small so that a sufficient extinction coefficient is obtained. Thus, the following equation is defined:

\[ FOM = \frac{\text{E}_{\lambda} - \text{E}_{\lambda}}{\text{E}_{\lambda} + \text{E}_{\lambda}} \]  

Where T(E) shows the transmission of IB-T in ISB-T energy, E1 and E2 show low and high ISB-T energies, respectively. The solid line shown with dots in figure 6b shows FOM based on the results of an experiment. There is a maximum point for ISB-T energy at point 0.49 pJ/μm, which at this operational point the output signal levels have been summarized that are shown in figure 6c, which is in fact the truth table obtained for NAND. Also the extinction coefficient was considered very low and at 20db. Moreover, using a blade or mesa waveguide that has a relatively high optical limit can be used instead of the 45° multi-sided reflection geometry for increasing the efficiency of modulation. Also the transmission efficiency is obtained through the following equation:

\[ \frac{dI_{\text{IBT}}(Z)}{dz} = \left( \frac{I_{\text{IBT}}(Z) - \text{E}_{\lambda}}{I_{\text{IBT}}(Z) + \text{E}_{\lambda}} \right) \cdot I_{\text{IBT}}(Z) \]

\[ \frac{dI_{\text{IBT}}(Z)}{dz} = \left( \frac{I_{\text{IBT}}(Z) - \text{E}_{\lambda}}{I_{\text{IBT}}(Z) + \text{E}_{\lambda}} \right) \cdot I_{\text{IBT}}(Z) \]

I(Z) shows the power density in the state of Z at waveguide length and Jsat shows the density of saturated absorption capacity. Also, α and β are absorption coefficient and two-photon absorption coefficient, respectively and factor Γ is optical limit. The ISBT and IBT indices in I and α determine the ISBT and IBT light resonant. Here, a power density has been defined as energy pulse density, which we consider at a time of 130 fs through a split pulse. The curve available in figure 6a and 6c presents filled-curves that have been derived from the above-mentioned model, which conforms with the experiment results very well. Through a waveguide with a length of 200 μm may improve the transmission of IB-T that has been done by I_{IBT} (200 μm) I_{IBT} (0 μm) up to 15db in an ISBT with an input energy density of 0.49 pJ/μm, which has been clearly shown in figure 6c. There are two types of skews in a two-input system:

1. Skew between ISBT and IBT resonant signals
2. Skew between ISBT signals

which these have been schematically shown in figure 6a with t1 and t2; respectively. We will discuss the acceptable skewness value based on a simple model, when two inputs are in High (on) state. The transmission change in IB-T light resonant through the convolution of the resulted optical curve and the device's impulse response have been modeled. The resulted ISB-T light resonant in the device has been modeled by the addition of a rectangular pulse with a width of 100fs. The device's impulse device has been modeled with exp (-t/880/fs) based on the experiments' results shown in figure 4b. The IBT input rate as a time integral from producing ISBT resonant inputs that are 100 fs rectangular pulses and the device's induction transmission were considered.

Figure 6a: IB-T Resonant Light Transmission as a definition for extinction coefficient
Figure 6b: FOM; Density function of ISB-T resonant input energy
Figure 6c: Transmission improvement rate in waveguide structures
CONCLUSION
In this article, a method for a high-speed all-optical processing particularly for NAND gates based on the energy transmission in tolerance and conductance bands of semiconducting quantum wells has been suggested. The results of practical experiments and comparing them with theoretical calculations indicates that using double quantum well not only increases the processing speed, but it also provides the permission for working in telecom wavelengths. Also, comparing experimental experiments results with other methods showed that using double quantum well in addition to the speed increase and volume and dimensions' decrease, it does not have the problems of other proposed methods of optical logic gates fabrication, such as large final period, non-linear performance, and low operational speed due to large transmission period. It is hoped that in future researches by studying other combined semiconductors at telecom wavelengths in a broader range, higher operational speed and easier designs for other logic gates and operators are obtained.

REFERENCES