Novel NAND and AND Gate Using DNA Ligation and Two Transistors Implementations

Himanshu Thapliyal[1] , A.Rameshwar[2], Rajnish Bajpai[2] and Hamid R. Arabnia[3]
(rameshwar_a@iiit.net, thapliyalhimanshu@yahoo.com, rajnish@students.iiit.net, hra@cs.uga.edu)
[1]Centre for VLSI and Embedded System Technologies
[2]Bioinformatics Research Center
International Institute of Information Technology Hyderabad, India
[3]Department of Computer Science, The University of Georgia, U.S.A

Abstract— **In this paper, novel NAND and AND gates are proposed using standard operations on DNA strands in presence of ligase enzyme. The NAND gate is realized as it is a universal gate and any Boolean function can be implemented through it. Thus, this paper provides an initial threshold to realize components of primitive DNA computers. From the VLSI perspective, this paper also proposes novel two transistors AND & NAND gates. The proposed AND gate has no power supply, thus it can be referred as the Powerless AND gate. Similarly, the proposed two transistor NAND gate has no ground and can be referred as Groundless NAND.**

I. INTRODUCTION

In the molecular computing, particular molecules are used as information carriers. Ever since the ground-breaking demonstration of the use of recombinant DNA technologies to solve the Hamiltonian path problem for a simple graph by Adleman in 1994, efforts are on to make DNA computing more practicable[8]. It is in a very early stage of development, but seems very promising.

The first step consists of developing basic binary devices like logic gates. Boolean operators like AND, OR and NOT are the fundamental operations on any computer. The basic logic gates can be constructed by putting together DNA strands in biochemical reactions.

The implementation of logic gates through biochemical reactions have been considered as an exciting and promising problem [1,2,4,6,7]. Mulawka et al (1999) implemented a logic NAND gate using standard operations on DNA strands as well as digestion by the restriction nuclease class II [3]. Recently NOT, AND and XOR gates have been constructed using synthetic deoxyribozymes(5). Further manipulation of DNA using the known biochemical properties can hasten the development of DNA computing.

The DNA strand is a polymer chain of nucleotides adenine (A), thymine (T), guanine (G) and cytosine (C), having its polarity from a 5’ end to 3’ end. Among the DNA strands, the process of bonding happens by the linking of the complementary pair of bases: A to T and G to C. The two complementary strands will only bind together, if they have opposite orientations of 5’ and 3’ ends.

Furthermore in the current VLSI scenario, to satisfy the Moore’s law and the high speed processing needs, more logic elements are packed into smaller volumes and are clocked at higher frequencies, dissipating power in form of heat. This huge dissipation of power in form of heat leads to exhaustion of batteries of portable systems and systems overheat [9]. Thus, today there is an increasing need of the portable applications requiring small-area, low-power and high throughput circuitry.

This paper proposes a novel AND and NAND gates using two strands of DNA, I_1 and I_2, working as the inputs of a NAND or AND gate. The biochemical reaction will occur in the presence of the glue strand and the ligase enzyme. The primary objective of this contribution is to show how the DNA strands can be realized to perform the logic operation. Furthermore, NAND gate is specially designed using DNA strands, since it is a universal gate and any Boolean function can be realized through it.

To satisfy the constraint of small-area low-power high throughput circuitry, this paper also proposes novel two transistors AND & NAND gates. The proposed two transistor AND & NAND gates have only either VDD or GND, thus preventing the flow of short circuit current. Thus, novel small area low power high throughput circuitries are proposed with bare minimum of two transistors.

II. DNA LIGATION

Ligation is joining of linear DNA fragments together with covalent bonds. In the DNA ligation, a phosphodiester bond is created between the 3' hydroxyl of one nucleotide and the 5' phosphate of another. T4 DNA ligase is the enzyme used to ligate DNA fragments. The process of ligation is shown in Figure 1. In order to connect strand I_1 to strand I_2, a “glue strand” (I_1 complement and I_2 complement) is used to bring the two strands into proximity through annealing. Finally, the ligase enzyme is added to fuse the two strands together.

Start with two stretches of non complimentary input strands (I_1 and I_2). Nearly one half of the glue strand must be complimentary to the free end of I_1 and the second half to the free end of I_2 (Quencher and dye attached to the other ends of the two strands respectively. See section IV). When annealed properly, all three will be coming together at the appropriate places due to the formation of hydrogen bonds between bases of input strands and the glue strand. Only when 3'-OH end of I_1 which is the substrate for attachment of the 5'-phosphate of the incoming nucleotide of I_2 is positioned correctly side by side, ligase seals the nick in one strand of duplex DNA (i.e. between I_1 and I_2) resulting in a longer chain $I_1 + I_2$.

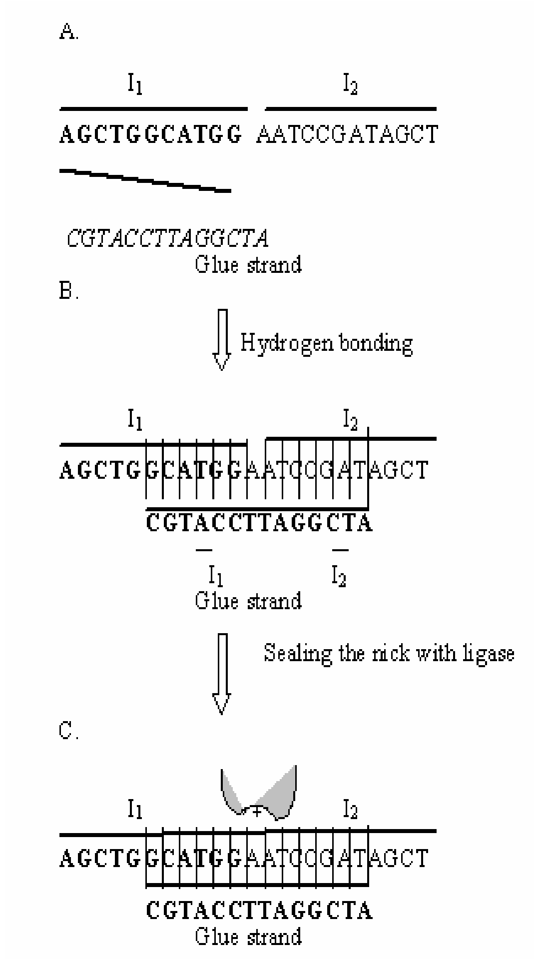

Figure 1. A. Two input strands I_1 and I_2. which are noncomplimentary and a glue strand
B. As the first half of glue strand (I_1 compliment) is complimentary to the end of I_1 and second half (I_2 compliment) complimentary to the end of I_2, Hydrogen bonding occurs between the complimentary pairs resulting in a double strand with a nick
C. Only then ligase enzyme seals the nick between A of I_1 and A of I_2.

III. NAND GATE REALISATION USING DNA LIGATION

The truth table of the NAND gate is shown in the Table 1 where I_1 and I_2 are the inputs and ($I_1 + I_2$) represents the output. Now consider the ligation reaction in Figure 1, having the inputs represented by two strands of DNA I_1 and I_2, glue strand represented by I_1 complement and I_2 complement (represented by bars in Figure 1). The ligation will occur when DNA strands I_1 and I_2 are complementary to glue strand (I_1 complement and I_2 complement). The phenomenon of occurrence of ligation is considered as generating the output $I_1 + I_2$ as ‘0’ while the non occurrence is considered as generating the output $I_1 + I_2$ as ‘1’.

TABLE I. TRUTH TABLE OF NAND GATE

I_1	I_2	$(I_1+ I_2)$
0	0	1
0	1	1
1	0	1
1	1	0

The proposal of the NAND gate using ligation reaction in Figure 1 is explained below.

CASE I: When both I_1 and I_2 are not complementary to the glue strand I_1 complement and I_2 complement respectively. In this case, the ligation reaction will not occur and can be considered as generating the output ‘1’ matching the truth table of the NAND gate.

CASE II: When I_1 is not complementary to glue strand I_1 complement but I_2 is complementary to glue strand I_2 complement. In this case, the ligation reaction will not occur and can be considered as generating the output ‘1’. This also matches the truth table of the NAND gate.

CASE III: When I_1 is complementary to glue strand I_1 complement but I_2 is not complementary to glue strand I_2 complement. In this case, again the ligation reaction will not occur and can be considered as generating the output ‘1’, matching the truth table of the NAND gate.

CASE IV: When I_1 is complementary to glue strand I_1 complement and I_2 is complementary to glue strand I_2 complement. In this case, the ligation reaction will occur and can be considered as generating the output P as ‘0’ matching the truth table of the NAND gate.

Thus, it can be verified that the NAND gate can be realized easily using the DNA ligation reaction. Since the AND gate is complementary to the NAND gate, taking the reverse convention, the proposed approach can also work as an AND gate (by considering the phenomenon of occurrence of ligation as generating the output $I_1 + I_2$ as ‘1’ while the non occurrence is considered as generating the output $I_1 + I_2$ as ‘0’).

IV. IMPROVED DETECTION OF OUTPUT MOLECULES

This technique can be further improved by tagging with fluorescent dyes. The dye can be tagged to the end of one input strand (I_1) and a quencher to the end of the second input strand (I_2). Ligation can be easily noticed with reduced fluorescence along with increased size of the oligonucleotide chain.

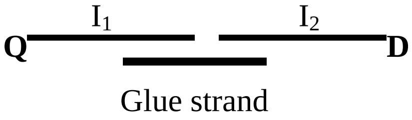

Figure 2. Adding the fluorescent tag. Q = Quencher , D = Flurescent dye. Initially I_1 with Q has no fluorescence. I_2 with D is highly fluorescent When ligated together, the longer chain will have a reduced fluorescece than what I_2 has when it was not attached

V. TWO TRANSISTOR AND/NAND GATES

In this paper, novel two transistor AND and NAND gates are proposed. The proposed two transistors AND gate is shown in Figure 3. It has no power supply, thus it can be referred as the Powerless AND gate. Similarly, two transistor NAND gate is proposed as shown in Figure 4, having no ground and can be referred as Groundless NAND gate. It is to be noted that proposed NAND gate is active low input gate. The proposed NAND gate can also work as OR gate when inputs are active high. The proposed designs are one of the most optimal designs of the AND & NAND gates which are directly scalable to higher inputs by cascading.

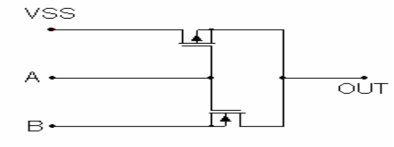

Figure 3. Proposed Two Transistor AND Gate

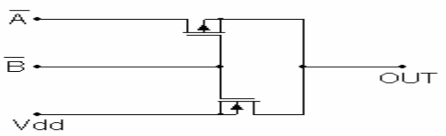

Figure 4. Proposed Two Transistor Active Low NAND Gate

The following equation [10] is used to estimate the power consumption of a circuit.

$$P_{Dynamic} = (\sum_i C_i * V_{i\_swing} * P_i) * f_{clk} + i_{sc} * VDD + \sum_i i_{leak} * VDD$$

In the above equation, $P_{Dynamic}$ is the power consumption, C_i is the load capacitance, V_i is the voltage swing, P_i is the probability of a switch, f_{clk} is the clock frequency, I_{sc} is the short-circuit current, I_{leak} is the leakage current and VDD is the supply voltage. It can be inferred from the above equation that the main components of the power dissipation are the I_{sc} and V_{swing} components. Since, the I_{leak} component in the equation is usually very low and is generally discarded. The voltage swing of a circuit is referred as the change in voltage during a transition and is equal to the voltage difference between logic '1' and logic '0' [12]. The reduction in voltage swing results in lower power dissipation [12] and there is a reduction in the voltage swing when the signals are not fully transmitted (when NMOS transmits logic '1' or a PMOS transmits logic '0')[12].

The proposed AND & NAND gates have incomplete voltage swings since in the proposed AND gate (Fig. 3) PMOS is permanently tied to logic '0' and in the proposed NAND gate (Fig. 4) NMOS is permanently tied to logic '1'. Moreover, since the proposed gates have only either VDD or GND, neither both in the same circuit, there is no short-circuit current established by a direct path between VDD and VSS. Thus the proposed gates are highly optimized in terms of power consumption.

V. CONCLUSIONS

In this paper, the authors have proposed an approach to realize the NAND and AND gates using DNA ligation reaction and also with optimal two transistor implementations. The approach is functionally verified using the Truth Tables of the AND & NAND gates. It is expected that the proposed approach will provide a platform to realize logic gates using biochemical reactions and also optimally using transistors.

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