Carbon Dots-Based Logic Gates

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Contributor: Dror Fixler

Carbon dots (CDs)-based logic gates are smart nanoprobes that can respond to various analytes such as metal cations, anions, amino acids, pesticides, antioxidants, etc. Most of these logic gates are based on fluorescence techniques because they are inexpensive, give an instant response, and highly sensitive

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1. Introduction

CDs based logic gates can be categorized based on their displayed logic output. For this review purpose, we have categorized the CDs based logic gates as single output, combinational output, sequential output, and reversible systems (Figure 1).

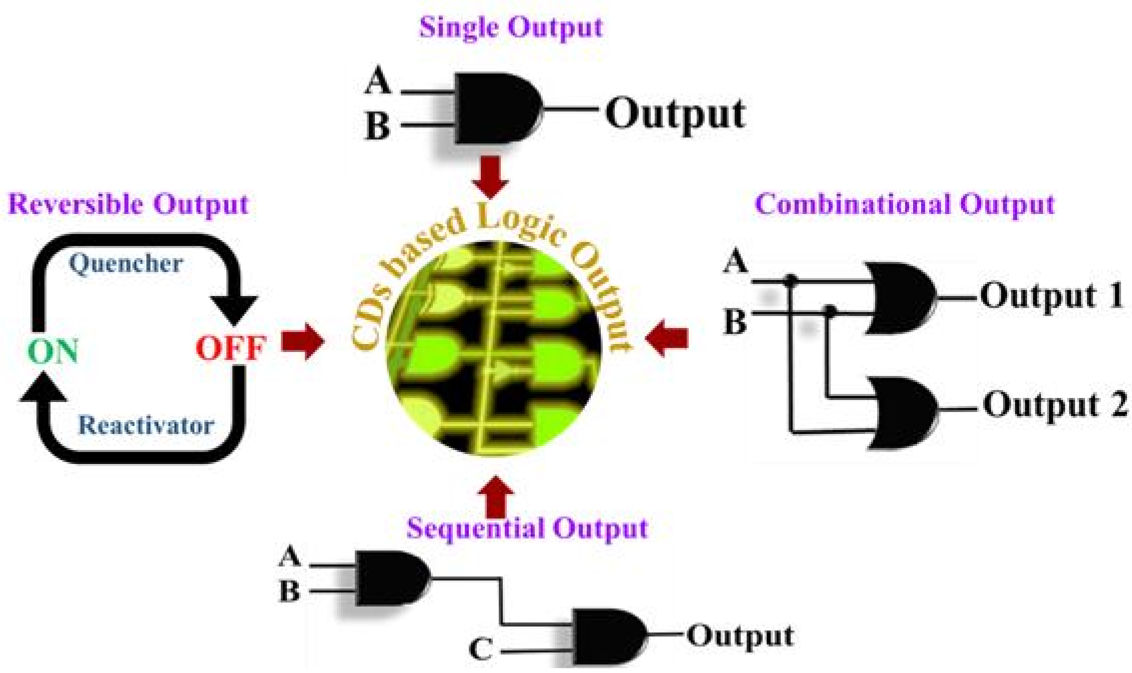

Figure 1. Different categories of carbon dots (CDs)-based logic gates according to their output. I. Single output, where only one output is generated. II. Combinational outputs are the integration of simple logic operations to obtain the complex combinational output. III. Sequential output, which responds to multiple inputs but with different stages of activation that should happen in a predestined order. IV. Reversible systems can switch between ON and OFF states depending upon the input added to the system.

2. Single Output

The single output is the basic building block of CDs based logic gates. It is important to establish a complex logic function based on these simple single-output logic operations. This type of system responds to multiple inputs to give a single response. Due to the simplicity of these systems, many researchers have used CDs as fluorophores for developing CDs based logic gates. Lin et al. have demonstrated different logic functions such as YES, OR, NOT, XOR, and IMP based on the sensing properties of CDs with metal cations and anions. These multiple logic gates are created through sequential metal ion association and anion dissociation process with CDs[1]. Zhao et al. constructed an AND logic gate with AgNPs nitrogen-doped CD nanocomposites without any chemical labeling and complex modification[2]. There are several reports that have constructed AND logic operation through the detection of different metal ions, such as Cr^{6+}[3], Hg^{2+} [4], Cu^{2+}[5], and Fe^{3+}[6]. Apart from AND, other logic operations such as the INHIBIT function were also fabricated through sensing of various metal ions through different amino acid derivatized CDs[7], histidine[8], Cu^{2+}, H_2S[9], arginine, and acetaminophen[10]. Other researchers developed IMPLICATION logic operations using the sensing ability of CDs for Hg (II) and cysteine[11], AA[12], Fe^{3+}[13], Hg^{2+}, and biothiols[14], Hg(II), and glutathione[15]. A multilevel single-output logic system was also developed using gadolinium doped CDs with H^+, OH^-, Cu^{2+} as inputs, which trigger both Fluorescence intensity (FI) and magnetic resonance (MR) signals[16]. Apart from the fluorescence technique, using magnetic resonance signal for dual readout logic operations is of significant importance, as the combination of FL/MR techniques gives the logic devices better applicability in case of biological application.

3. Combinational Logic Output

The output of the combinational logic operation is the instant response to their current input state as logic 0 or logic 1. This type of output depends upon the combination of the input all the time. Thus, the combinational logic circuit is termed as ‘memoryless’. Combination logic circuits combine or connect simple logic operations to build a complex logic circuit. Tang et al. demonstrated the combinational nano logic gate with a dual output channel. The supramolecular assembly based on CDs showed two distinctive patterns of logic function at two different emission wavelengths of 440 nm and 490/545 nm. The output channel at 490/545 nm consists of a combination of two INHIBIT gates[17]. The supramolecular strategy serves as a substitute for covalent modification and simplifies the fabrication process. Zhao et al. performed half addition and half subtraction operations on synthesized pH-responsive CDs at two different emission wavelengths. A half-adder was constructed by combining XOR and AND gates, which further implement the function of sum and carry, while the half-subtractor consisted of the INHIBIT gate producing borrow bits and XOR gate for obtaining difference bits[18]. Fan et al. have designed a three-input and three-output combinational circuit along with a keypad lock using red emissive CDs/Prussian blue composite electrode films. The complicated logic gate was constructed using elementary functions such as OR, AND, INHIBIT, and IMP[19].

4. Sequential Output

Unlike combinational output, the third category is the sequential output in which the output depends on both present inputs and previous output. In contrast to combinational output, it has a memory, so the output varies based on the input. Qu et al. designed multiple single and sequential DNA-based logic gates. These types of logic gates were inspired by B to Z-DNA transition induced by functionalized CDs. The logic gate was constructed based on FRET between CDs and DNA intercalators and fluorescence quencher for CDs. Single AND functions were established at 585 nm and NAND logic at 465 nm. Similarly, AND + INHIBIT and NAND + INHIBIT sequential circuits were constructed at 585nm and 465nm, respectively[20]. Fluorescence techniques have certain limitations, such as shorter emission lifetime of nanoseconds leading to inner filter emission (IFE), overlapping of excitation and emission spectra, interference from the light scattering, and short-lived autofluorescence species. These limitations can be overcome by the triplet excited state phenomena known as ‘Phosphorescence’. Wang et al. developed a phosphorescence-based OR-INHIBIT logic gate using inputs such as Hg(II), tDNA (target ssDNA), and doxorubicin[21]. The phosphorescence logic gates are superior to most common fluorescence-based logic gates due to their benefits over fluorescence. Viswanathan et al. used the switching nature of CDs to design memory devices having sequential circuits due to reversible response with the addition of Hg(II) and L-cysteine alternatively. A Write-Read-Erase-Read nature of sequential circuit was developed using OFF-ON reversible behavior with inputs as Hg (II) and L-cysteine[22]. Other research groups have reported integrative logic gates such as NOR and INHIBIT (INH) and IMPLICATION (IMP), NOR and AND logic functions. These logic gates have three inputs such as Zn(II), pH 2, and Cu(II) for NOR and INH and four inputs such as Zn^{2+}, S^{2-}, Cu^{2+}, and pH 2 for IMP, NOR, and AND logic operation[23]. Recently, an integrative logic system based on dual readout logic devices with both magnetic resonance (MR) and FI of holmium doped CDs was discussed by Fang et al. The multi-readout logic circuits were developed by recording the same signal by two different readout techniques. The chemical inputs were H^+, Fe^{3+}, and Fe^{2+}, while the fluorescence output was recorded at 440 nm along with magnetic intensity. A fluorescence-based NOR-INHIBIT and MR-based (XOR-INHIBIT)-OR sequential logic system was demonstrated successfully[24].

5. Reversible Output

The reversible system is interesting because it allows the reassessment of the output[25]. The advantage of this process is that the logic operation can be performed multiple times without adding more analytes constantly. The reversible system with the activated condition can revert to its original state with the introduction of a reactivator. CDs-based reversible logic gates work on the principle of quenching the FI signal, which further recovers by a recovery agent[9]. This type of logic gate is a potential candidate for low-power computing[26].

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