Electronic Supplementary Information (ESI)

Quantum dot-labelled aptamer/graphene oxide system for the construction of half-adder and half-subtractor with high resettability†

Xianyun Hu,[ab] Yuqian Liu[a], Xiaojun Qu,[a] and Qingjiang Sun*[a]

[a]State Key Laboratory of Bioelectronics, School of Biological Science & Medical Engineering, Southeast University, Nanjing 210096, P. R. China.

[b]Qiannan Medical College for Nationalities, Duyun 558000, P. R. China

*Fax: (86) 25-83792349; Email: sunqj@seu.edu.cn

1. Experimental procedures

1.1 Materials and reagents.

Graphene oxide (GO) was obtained from Aldrich. Adenosine triphosphate (ATP) and thrombin (Thr) were purchased from Sigma. The thiolated aptamers for ATP and Thr (referred to as ABA and TBA, respectively), and label-free aptamers (referred to as DNA1 and DNA2, respectively) were synthesized by Invitrogen (Shanghai, china), and their sequences are listed in Table S1.

1.2 Instruments.

Fluorescence spectra were collected with an F-7000 fluorescence spectrophotometer (Hitachi, Japan). UV/Vis absorption spectra were obtained by a Hitachi U-4100 spectrophotometer. Transmission electron microscopy (TEM) images were taken on a JEOL JEM-2100 microscope. Circular dichroism (CD) spectra were obtained with a Chirascan circular dichroism spectrophotometer (Applied Photophysics, UK).

1.3 Labelling Aptamers with QDs.

Water soluble dual-coloured InP/ZnS QDs (QD_{506} and QD_{571}) were synthesized in our lab. The labeling was accomplished *via* typical ligand-exchange method. Briefly, for labeling TBA, 2 μM of QD_{506} was mixed with 10 μM of thiolated TBA in Tris-HCl buffer (10 mM Tris-HCl, 30 mM NaCl, pH 8.0) and stirred for 48 h at room temperature, followed by ultrafiltration at 7, 000 rpm for 10 min with 30 KDa

centrifugal filter. For labeling ABA, the same procedure was conducted, except that 0.3 μM of QD_{571} and 7.5 μM of thiolated ABA were used, respectively. The number of aptamer per QD was estimated by recording the change in the absorption of aptamer before/after the labeling.

1.4 Assembly of QD-aptamer/GO.

To assemble the system, TBA-QD_{506} (50 nM) and ABA-QD_{571} (30 nM) were first mixed together to achieve the QD_{506}-to-QD_{571} fluorescence intensity ratio of 1: 1. Afterwards, different concentrations of GO were added into the mixture solution and incubated for 20 min at room temperature, followed by centrifugation at 10, 000 rpm for 20 min. The precipitates were re-dispersed in Tris-HCl buffer (10 mM Tris-HCl, 100 mM NaCl, 2 mM KCl, pH 8.0) for fluorescence measurements. By recording the fluorescence quenching of QD_{506} and QD_{571} by GO, 30 μg mL^{-1} of GO was selected to assemble the logic system (see Fig. S1).

1.5 Half Adder and Half Subtractor Operations.

For the half adder operation, solutions of GO/TBA-QD_{506}/ABA-QD_{571} (10 mM Tris-HCl, 100 mM NaCl, 2 mM KCl, pH 8.0) were incubated with 1 equiv. of solutions of Thr (300 nM), ATP (300 μM), and Thr (300 nM) coexsited with ATP (300 μM), respectively. The fluorescence spectra were recorded, respectively, after 40 min for each of the incubations.

For the half subtractor operation, solutions of GO/TBA-QD_{506}/ABA-QD_{571} were incubated with 1 equiv. of solutions of Thr (300 nM) coexisted with DNA1 (200 μM), ATP (300 μM) coexisted with DNA2 (300 nM), and a mixture of Thr (300 nM), ATP (300 μM), DNA1 (200 μM), and DNA2 (300 nM), respectively. The fluorescence spectra were recorded, respectively, after 40 min for each of the incubations.

1.6 The pH Titration Experiments.

A mixture of GO/TBA-QD_{506}/ABA-QD_{571} with Thr (300 nM) and ATP (300 μM) was prepared in Tris-HCl buffer (10 mM Tris-HCl, 100 mM NaCl, 2 mM KCl, pH 8.5). The pH titration experiments were first conducted to adjust the solution pH to be 8.0, 7.5, 7.0, 6.5, 6.0, 5.5, and 5.0, respectively, by the addition of certain amounts of 1.0 M HCl. The fluorescence spectra were recorded, respectively, after 10 min for each

addition of HCl. Afterwards, the solution pH was reversely adjusted from 5.0 to be 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, and 8.5, respectively, by the addition of certain amounts of 1.0 M NaOH. The fluorescence spectra were recorded, respectively, after 40 min for each addition of NaOH.

1.7 Fluorescent Switch

For fluorescent switch, 100-cycle "set-reset" operations of pH were performed. For the "set" operation, the solution pH of a mixture of GO/TBA-QD_{506}/ABA-QD_{571} with Thr (300 nM) and ATP (300 μM) was adjusted to be pH 8.0 by addition of 1.0 M NaOH. The fluorescence was measured after 40 min of the addition of base. For the "reset" operation, the solution pH was adjusted to be pH 6.0 by the addition of 1.0 M HCl, and the fluorescence was measured after 10 min of the addition of acid.

1.8 Repetitious Arithmetic Operations.

For repetitious arithmetic operations, multi-cycled half adder-reset and half subtractor-reset operations were performed, respectively. The half adder/half subtractor operation was performed as described in section 1.5. The reset operation was performed by adjusting the solution pH to be pH 6.0, followed by isolation by centrifugation at 10, 000 rpm for 20 min. The precipitates were re-dispersed in Tris-HCl buffer (10 mM Tris-HCl, 100 mM NaCl, 2 mM KCl, pH 8.0) for next half adder/half subtractor operation.

2. Supporting Tables and Figures

Table S1. Sequences for the thiolated aptamers (TBA and ABA), DNA1 and DNA2.

Name	Sequences
thiolated ABA	5' HS-C6-ACCTGGGGGAGTATTGCGGAGGAAGGT-3'
thiolated TBA	5' HS-C6-AGTCCGTGGTAGGGCAGGTTGGGGTGACT-3'
DNA1	5' ACCTGGGGGAGTATTGCGGAGGAAGGT-3'
DNA2	5' AGTCCGTGGTAGGGCAGGTTGGGGTGACT-3'

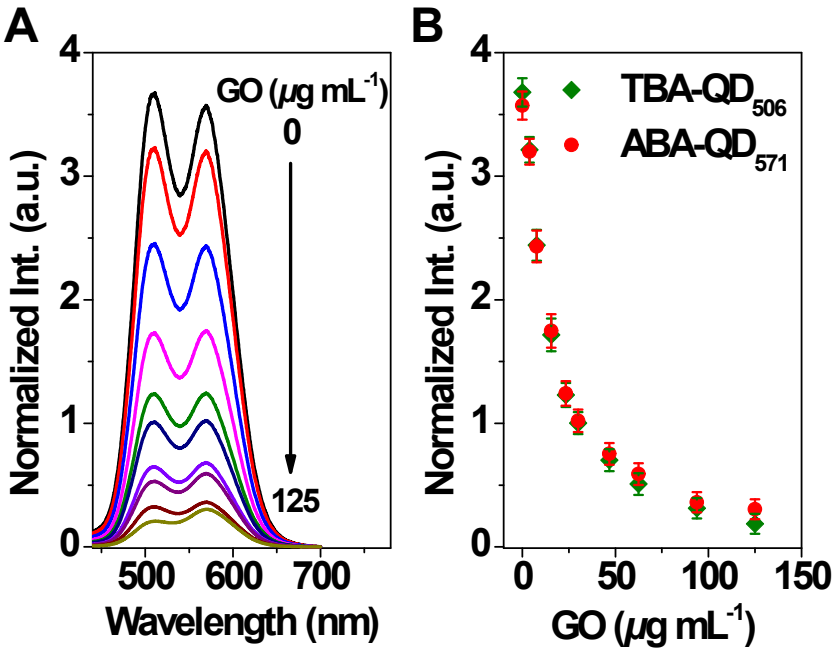

Fig. S1 (A) Fluorescence spectra of TBA-QD_{506} and ABA-QD_{571} in the presence of different concentrations of GO. The GO concentrations were 0, 4.0, 8.0, 16.0, 24.0, 30.0, 46.5, 62.5, 94.0, and 125.0 μg mL^{-1}, respectively. (B) Fluorescence quenching curves of QD_{506} and QD_{571} as a function of the GO concentration.

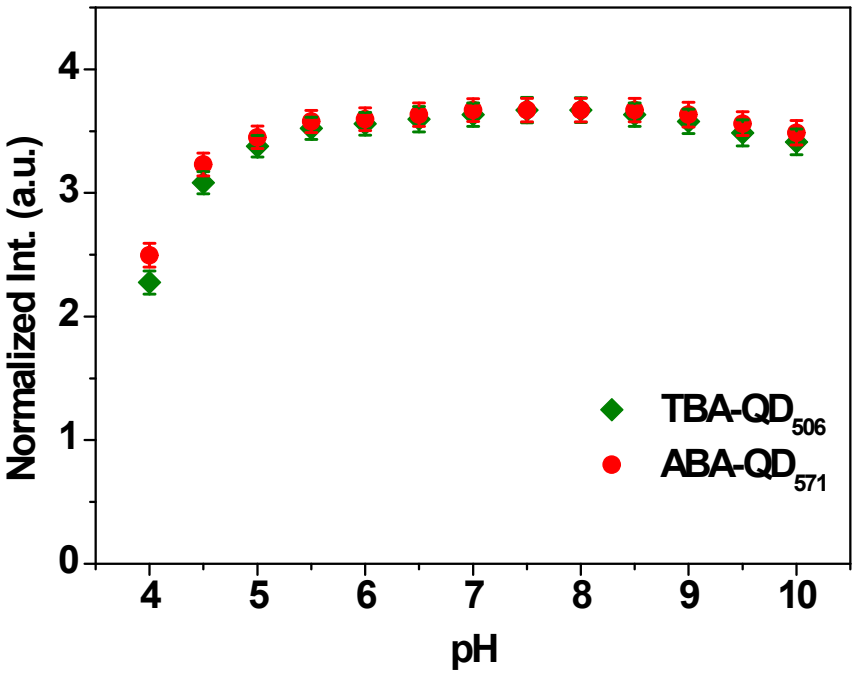

Fig. S2 Fluorescence stability of QD_{506} and QD_{571} at different pH.

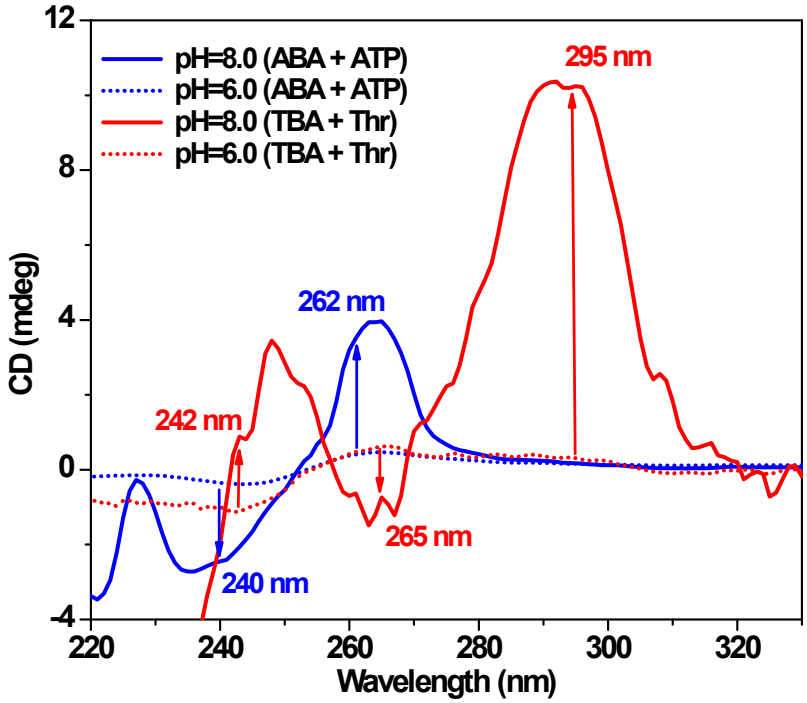

Fig. S3 The CD spectra of TBA in the presence of Thr, and ABA in the presence of ATP in buffer solutions of pH 8.0 and pH 6.0, respectively.

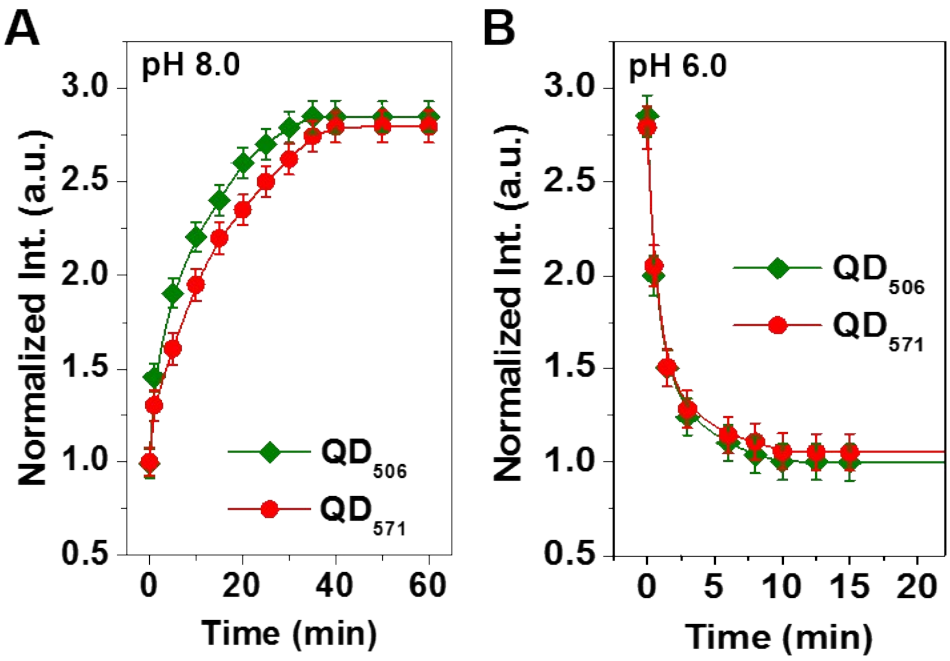

Fig. S4 (A) Kinetics for fluorescence recovery of GO/TBA-QD_{506}/ABA-QD_{571} in the presence of Thr and ATP as the solution pH was changed from pH 6.0 to pH 8.0. (B) Kinetics for fluorescence quenching of GO/TBA-QD_{506}/ABA-QD_{571} in the presence of Thr and ATP as the solution pH was changed from pH 8.0 to pH 6.0.

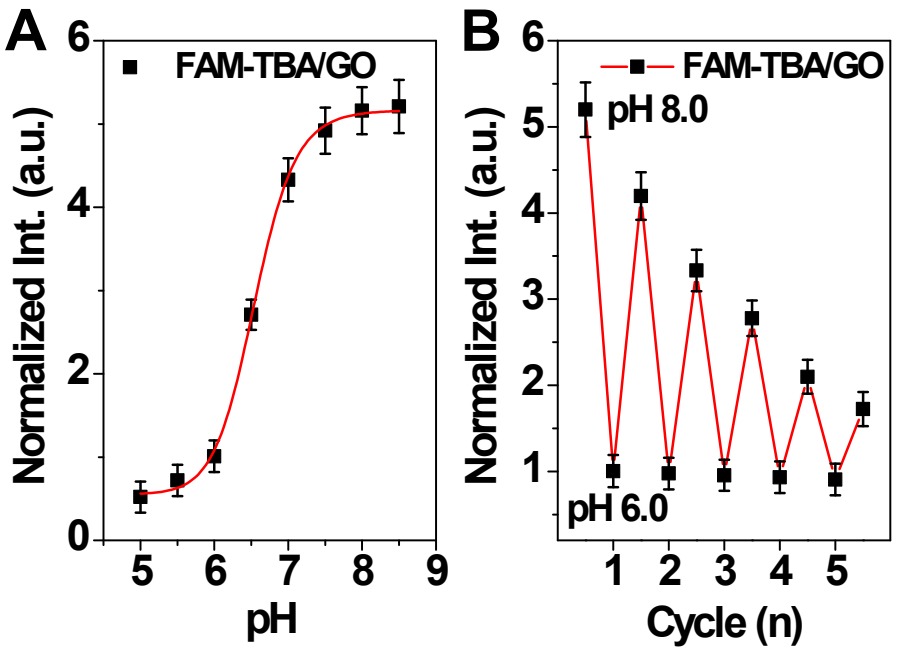

Fig. S5 (A) The fluorescent change of FAM-TBA/GO in the presence of Thr upon pH titration. (B) Fluorescent switching of FAM-TBA/GO triggered by acid-base neutralization.

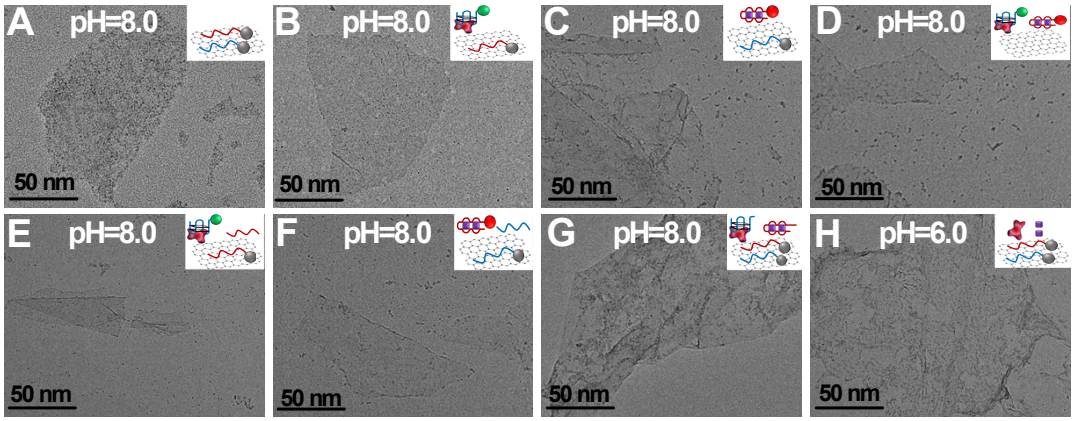

Fig. S6 TEM images of QD-aptamer/GO in the presence of various inputs: (A) none, (B) Thr, (C) ATP, (D) Thr and ATP, (E) Thr+DNA1, (F) ATP+DNA2, (G) Thr, ATP, DNA1, and DNA2. (H) The TEM image of QD-aptamer/GO in the presence of Thr and ATP (D) as solution pH was changed to be pH 6.0.

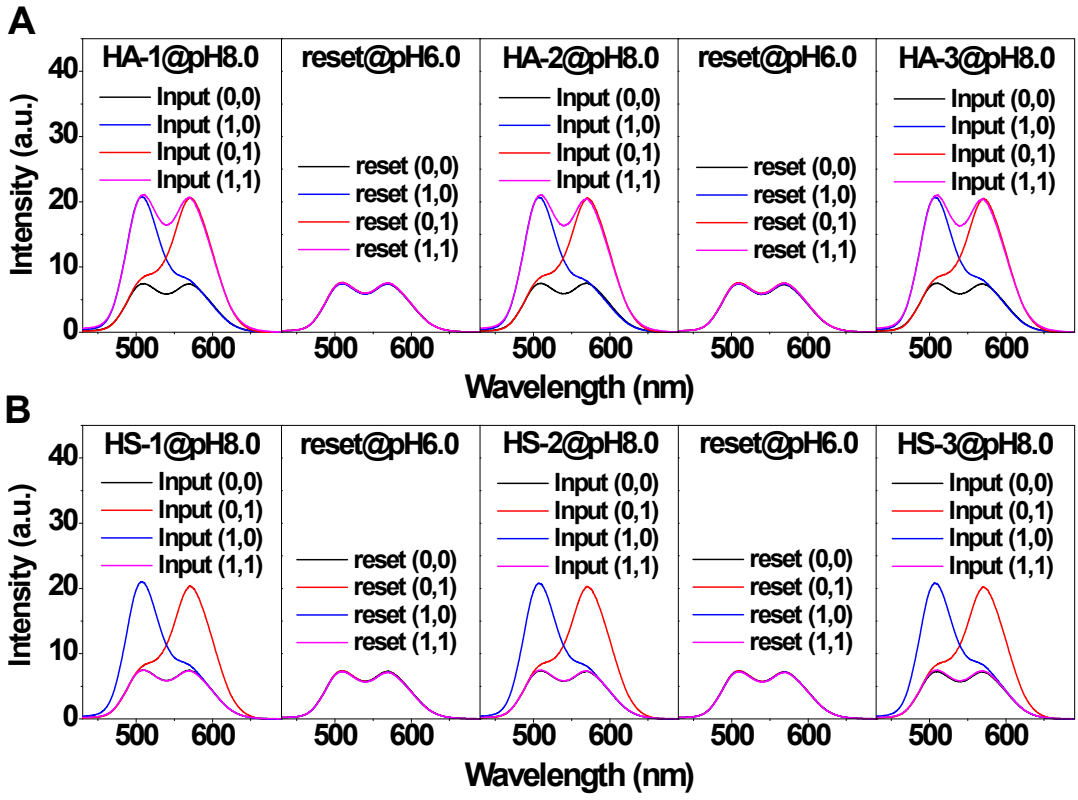

Fig. S7 Fluorescent spectra of (A) half adder-reset cycles and (B) half subtractor-reset cycles as triggered by various inputs.

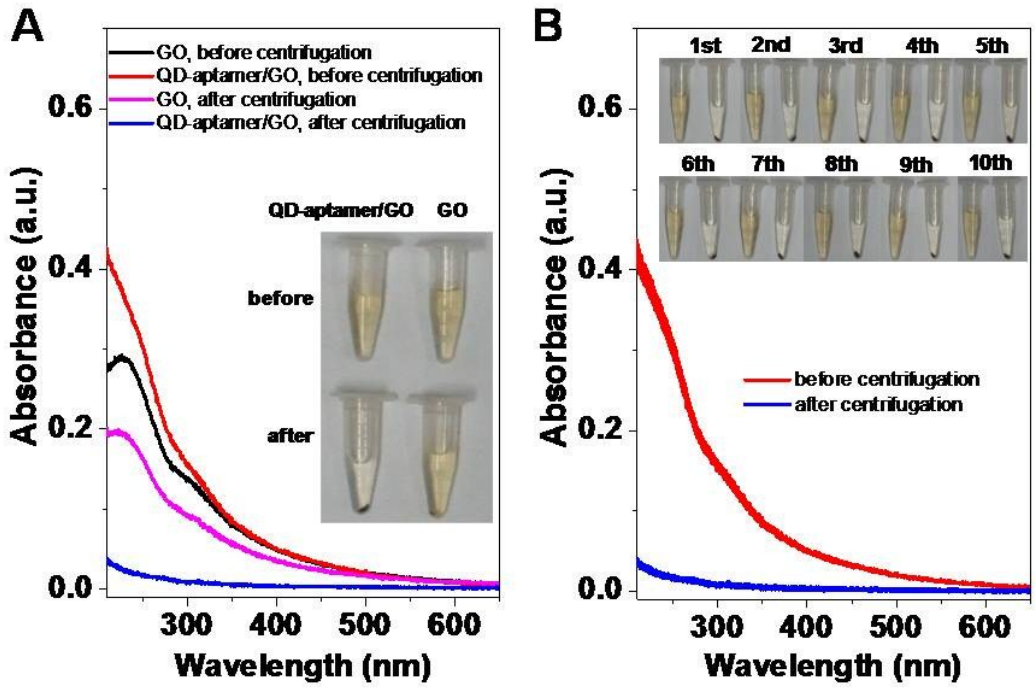

Fig. S8 (A) Absorption spectra of solutions of GO and QD-aptamer/GO at pH 6.0 before and after centrifugation. (B) The absorption spectra of one solution of QD-aptamer/GO for 10 cycles of "redispersion-centrifugation" operations at pH 6.0. The insets show the corresponding photographs.

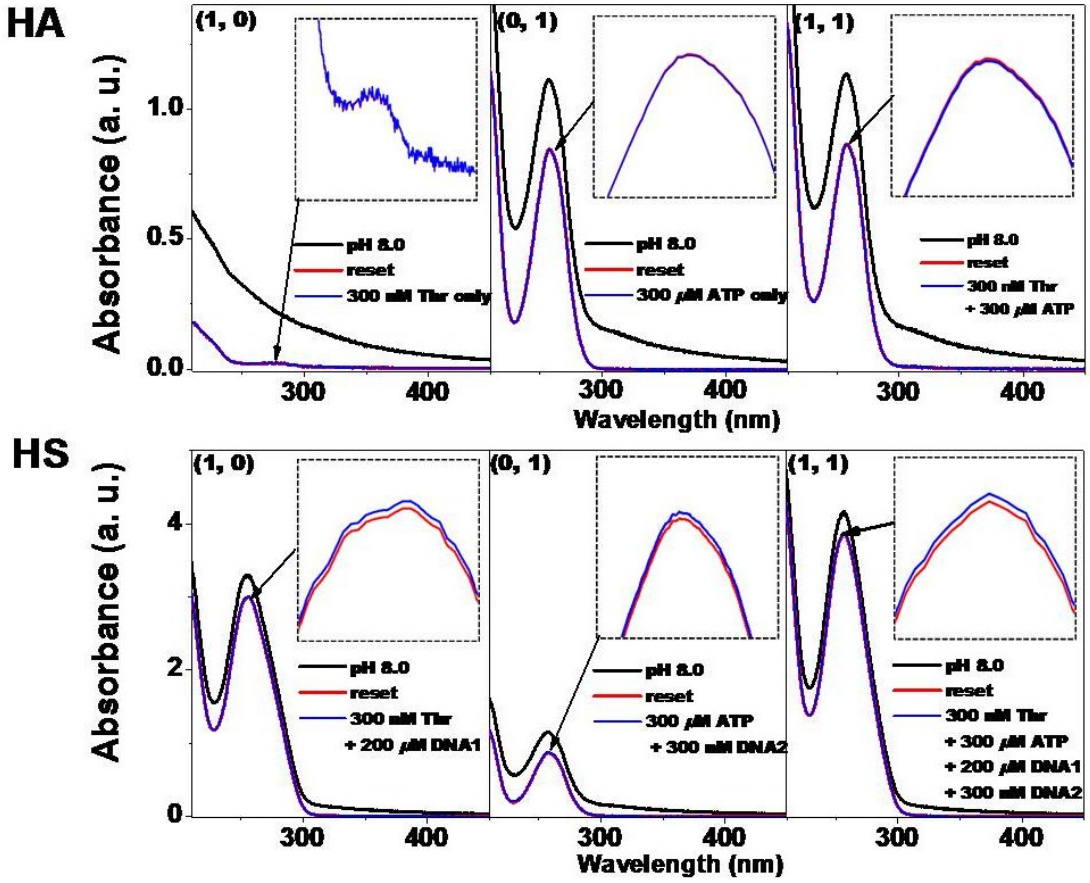

Fig. S9 Absorption spectra of solutions of QD-aptamer/GO for the HA-reset and HS-reset operations, respectively, as triggered by different inputs. The solutions of the input only in the absence of QD-aptamer/GO were used as the negative controls (blue lines).

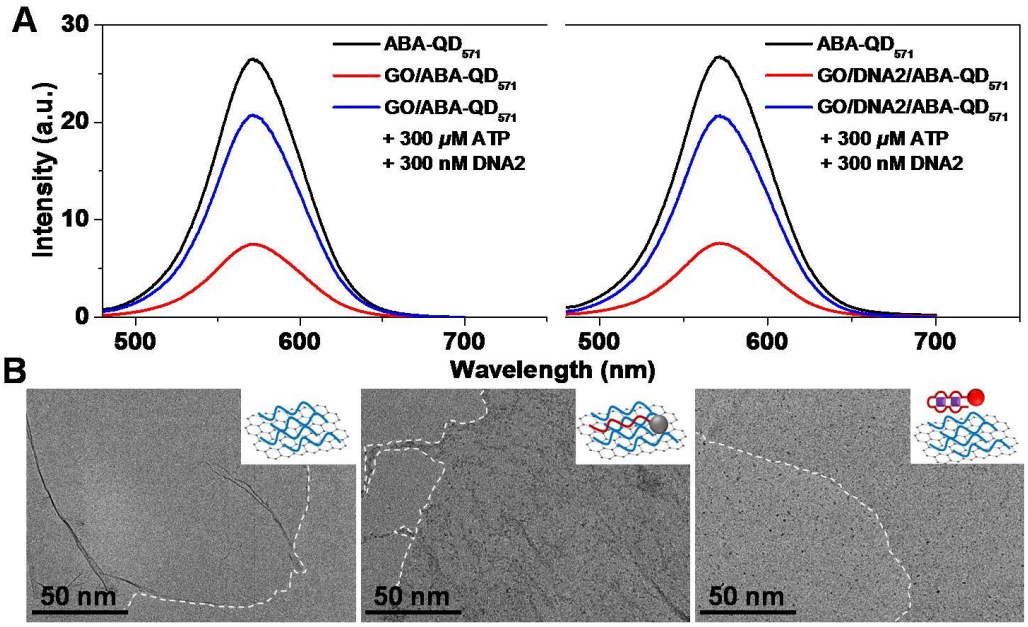

Fig. S10 (A) Fluorescence spectra of ABA-QD_{571} in the absence/presence of 30.0 μg mL^{-1} GO, followed by the addition of 300 μM ATP and 300 nM (left), and in the absence/presence of 30.0 μg mL^{-1} GO pre-mixed with 20 μM DNA2, followed by the addition of 300 μM ATP and 300 nM DNA2 (right). (B) TEM images of GO/DNA2, GO/DNA2/ABA-QD_{571}, and GO/DNA2/ABA-QD_{571} in the presence of 300 μM ATP and 300 nM DNA2.