(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 September 2006 (14.09.2006)

PCT

(10) International Publication Number
WO 2006/096185 A2

(51) **International Patent Classification:**
C12Q 1/68 (2006.01) *C12M 1/34* (2006.01)

(21) **International Application Number:**
PCT/US2005/011030

(22) **International Filing Date:** 25 March 2005 (25.03.2005)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
60/559,287 25 March 2004 (25.03.2004) US

(71) **Applicant** *(for all designated States except US)*: **THE GOVERNMENT OF THE UNITED STATES OF AMERICAN, AS REPRESENTED BY THE SECRETARY OF THE NAVY** [US/US]; Naval Research Laboratory, 4555 Overlook Ave, Sw, Code 1008.2, Washington, District Of Columbia 20375 (US).

(72) **Inventors; and**

(75) **Inventors/Applicants** *(for US only)*: **MEDINTZ, Igor, L.** [US/US]; 7800 Jansen Drive, Springfield, Virginia 22150 (US). **GOLDMAN, Ellen, R.** [US/US]; 10710 Watkins Rd., Germantown, Maryland 20876 (US). **ANDERSON, George, P.** [US/US]; 9105 Wipkey Ct., Bowie, Maryland 20720 (US). **MAURO, Matthew, J.** [US/US]; 4111 Dillard Road, Eugene, Oregon 97405 (US).

(74) **Agent: KARASEK, John**; NAVAL RESEARCH LABORATORY, 4555 Overlook Ave, Sw, Code 1008.2, Washington, District Of Columbia 20375-5325 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title: REAGENTLESS AND REUSABLE BIOSENSORS WITH TUNABLE DIFFERENTIAL BINDING AFFINITES AND METHODS OF MAKING**

(57) **Abstract:** The biosensor comprises a modular biorecognition element and a modular flexible arm element. The biorecognition element and the flexible arm element are each labeled with a signaling element. The flexible arm contains an analog of an analyte of interest that binds with the biorecognition element, bringing the two signaling elements in close proximity, which establishes a baseline fluorescence resonance energy transfer (FRET). When an analyte of interest is provided to the biosensor, the analyte will displace the analyte analog, and with it, the signaling module of the modular flexible arm, causing a measurable change in the FRET signal in an analyte concentration dependent manner. The modularity of different portions of the biosensor allows functional flexibility. The biosensor operates without additional development reagents, requiring only the presence of analyte or target for function.

REAGENTLESS AND REUSABLE BIOSENSORS WITH TUNABLE DIFFERENTIAL BINDING
AFFINITES AND METHODS OF MAKING

5

CROSS REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Number 60/559,287,
filed March 25, 2004.

10   TECHNICAL FIELD

Development of robust, sensitive, and reusable sensors is a strong current scientific
priority. As such, recognition-based biosensors capable of specifically detecting chemicals, toxins, and
bio-agents in their environment are of increasing importance. An important goal in biosensor evolution
is production of nanoscale assemblies capable of continuously monitoring concentrations of target

15   species in a simple, reliable manner. This is accomplished by designing sensor components to carry out
analyte recognition and binding while simultaneously producing useful output signals via an integrated
signal transduction system. Optically addressed biosensors of this type often employ fluorescence
resonance energy transfer (FRET) in signal transduction.

20   BACKGROUND ART

FRET has been employed in carefully designed sensing systems for proteins, peptides,
nucleic acids and other small molecules, see Medintz et al., *Nature Materials* 2003 2, 630. It is known in
the art that other sensing modalities can be employed in the signal read-out of recognition-based
biosensors, especially electrochemical modes or enzyme related systems, see Benson et al., *Science*

25   293,1641-1644 (2001).

Biosensors function by reversibly linking bioreceptor-target analyte binding with closely
integrated signal generation. Such sensors can either continuously monitor analyte concentrations or
easily be returned to baseline read-out values by removal of analyte. Current bioassays on the market are
single use or limited time use. Either they need to be replaced after each test or within a short time. This

30   increases both test costs and the logistical demands for performing the analysis. Fielded biosensors can
have complex robotics that handle the reagent storage and sensor surface replacement.

Sensor systems based on Surface Plasmon Resonance (SPR) can be regenerated, such as
the Biacore SPR instrument. This sensor works by measuring the change in index of refraction at the
sensor surface upon analyte binding. This works well for large molecules, but requires a harsh

35   regeneration fluid that limits sensor lifetime. In addition, it works poorly in complex samples where
nonspecific deposition to the surface interferes with the ability to discriminate actual signal.

Other systems can be used numerous times for the detection of small molecules, however

as the fluorescent analog is displaced off the sensor surface the sensor is slowly consumed until it no

longer functions. One example is the flow immunosensor of U.S. Patent No. 5,183,740 to Ligler, et al.

Surface acoustic wave sensors with selective membranes exist for the sensitive detection of

gas phase molecules. However, similar devices built for the liquid phase detection are less sensitive and

5   have the same limitations as SPR.

FRET based assays have previously been described; however they are fluid phase methods

that are effective for a single analysis only. This is also true for tests that depend on fluorescence

anisotropy measurements, which are effective solution phase analyses but require the reagents to be

freely moving to monitor a change upon binding.

10   A definition describing a biosensor has been proposed by IUPAC which provides that "a

biosensor is a self-contained integrated device which is capable of providing specific quantitative or

semi-quantitative analytical information using a biological recognition element (biochemical receptor)

which is in direct spatial contact with a transducer element. A biosensor should be clearly distinguished

from a bioanalytical system which requires additional processing steps, such as reagent addition.

15   Furthermore, a biosensor should be distinguished from a bioprobe which is either disposable after one

measurement, i.e. single use, or unable to continuously monitor the analyte concentration". Although

biological recognition elements are employed in an extensive range of analytical formats, in few cases

are they integrated into sensing devices and meet all these rigorous criteria.

The functional simplicity afforded by biosensors, allowing autonomous and continuous

20   monitoring of chemical species, promises to make these devices useful in chemical process monitoring,

pharmaceuticals screening, patient point-of-care and environmental testing, public health, and in defense-

related fields.

Optically addressed molecular biosensors that meet the above criteria have been developed

by Hellinga et al., *Proc. Natl. Acad. Sci. USA* 1997, *94*, 4366-4371, in which bacterial periplasmic

25   binding proteins (bPBPs) were engineered to allow transduction of binding events to remote fluorescent

signal-generating sites within the same protein by allosteric coupling. Recently, this strategy has been

extended to allow surface tethering to unmodified hydrophobic surfaces of dye labeled-bPBPs by

engineering of a self-adhering hydrophobic peptide onto the protein terminus, see Wada, et al, *J.A.C.S.*

2003, 52, 16228-16234.

30   FRET-based fusion protein biosensors that employ different colored green fluorescent

protein (GFP) mutants linked to substrate binding domains that report binding events by coupled changes

in conformation and energy transfer have also been developed, see Fehr, et al, *Proc. Natl. Acad. Sci.*

USA 2002, 99, 98469851, and Fehr et al, *J. Biological Chem.* 2003, 278, 19127-19133. Both of these

biosensor types are only useful for a small range of analysis targets. In the bPBP-based sensors,

35   intramolecular transduction of binding events to integrated signaling centers requires highly specialized

allosteric receptors. Even though computationally intensive redesign of the binding sites for recognition

of alternate substrates may be feasible, binding pocket remodeling is unlikely to prove practical in

providing sensors useful for monitoring a wide range of analytes. In sensors employing GFP fusion proteins, where differences in FRET efficiency between bound- and analyte-free receptor states result in signal generation, the range of bioreceptors that undergo obligatory ligand-dependent conformational changes is also very limited.

5   A variety of sensitive FRET-based single-measurement bioanalytical systems or bioprobes have been developed that detect peptides, proteins, and various small molecules in vivo and in vitro. See Scheller, et al, *Biotech.* 2001, 12, 35-40; Iqbal, et al, *Biosens. Bioelect.* 2000, 15, 549-578; O'Connell, et al, *Anal. Lett.* 2001, 34,1063-1078; and Marvin, et al *Proc. Natl. Acad. Sci. USA* 1997, 94, 4366-4371. Maxwell, et al, *J. Am. Chem. Soc.* 2002, 124, 9606-9612, describes a gold nanoparticle-nucleic acid
10   FRET biosensor that utilizes a probe DNA oligo in a 'molecular beacon' function to detect other DNA.

        Biosensors that utilize FRET are also attractive due to the intrinsic sensitivity of FRET to small changes in donor-acceptor distance and orientation. Medintz, et al, *Bioconjugate Chem.* 2003, 14, 909-918 demonstrated the feasibility of using dye-labeled MBP and dye-labeled β-CD for FRET-based detection in solution. Rather than being a sensor, that homogenous system functions only in single-
15   measurement bioanalysis.

DISCLOSURE OF THE INVENTION

        This invention provides a FRET-based surface-bound biosensor that overcomes the single-use limitation of previously known homogenous bioanalytical systems. The invention provides for fully
20   reversible, reagentless, self-assembling biosensors. It is an object of the present invention to provide a biosensor design that can easily be adapted to target different analytes. It is another object of the invention to provide a biosensor that has a modular design for incorporating a wider range of available receptors as bio-recognition elements. It is a further object of the invention to provide a biosensor that uses multifunctional surface-tethered components. It is a further object of the invention to provide a
25   biosensor that is regenerable or can operate in a continuous mode. These and other objects are provided by the invention disclosed below.

        The biosensor of the present invention comprises a modular biorecognition element and a modular flexible arm element that reacts with the biorecognition element. The biorecognition element is tethered to a substrate and can be a protein, an aptamer, a carbohydrate, DNA or RNA molecule, among
30   others. This biorecognition element is labeled with a fluorescent dye. The modular flexible arm is also tethered to a substrate, in an orientation that allows it to interact with the biorecognition element. The flexible arm contains an analog of the analyte that binds with the biorecognition element. Both elements are labeled with a fluorescent dye. When the elements bind, the dyes are brought in close proximity, which establishes a baseline fluorescence resonance energy transfer (FRET). When an analyte of
35   interest is provided to the biosensor, the analyte will displace the analyte analog. The displacement of the analyte analog by the analyte will cause a change in the FRET signal in a concentration dependent manner. The sensor of this invention can be regenerated and returned to baseline levels by washing away

analyte. A complex set of interactions exists on the sensing surface that contributes to overall sensor behavior and largely determines sensor dynamic range. This modular biosensor approach provides a way to assemble a wide range of useful biosensors that are regenerable, can be reused numerous times, or operated continuously and independently. Facile control of binding constants and sensing range is a

5   built-in capability. The modularity of different portions of the biosensor allows functional flexibility. The biosensor is adaptable to measure many different analytes or targets. The biosensor operates without additional development reagents, requiring only the presence of analyte or target for function.

       The recognition-based sensors of this invention are capable of specifically detecting chemicals, toxins, and bio-agents in their environment. These sensors employ a multifunctional

10   molecular assembly in which a surface-immobilized biorecognition entity can reversibly bind to a surface-tethered entity immobilized on the same or suitably closely situated surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts a schematic of the modular biosensor.

15   FIG. 2 depicts the structure of a modular arm of the MBP biosensor.

FIG. 3 shows the structure of the dye-labeled TNB DNA arm.

FIG. 4a shows a schematic of the MBP biosensor in its resting state

FIG. 4b shows a schematic of the MPB biosensor in the presence of an analyte

FIG. 5a shows a schematic of the TNT sensor in its resting state

20   FIG. 5b shows a schematic of the TNT sensor in the presence of analyte

FIG. 6 is a series of graphs depicting the change in fluorescence in relation to analyte concentration.

FIG. 7 is a graph depicting the change in fluorescence in relation to analyte concentration, demonstrating the effect of controlling binding properties when the flexible arm is stiffened with DNA.

FIG. 8 is a series of graphs depicting the change in fluorescents in relation to analyte concentration.

25

MODES FOR CARRYING OUT THE INVENTION

FIG. 1 depicts a schematic of a modular biosensor of the present invention. The biorecognition element (10) and the modular arm element (20) are tethered to a surface (30) by specific

30   oriented surface attachment module (40). The surface attachment modules (40) includes, but are not limited to, biotin, avidin, antibody, reactive thiol, reactive amine, non-reversible enzyme substrate, protein A, protein G, protein L, DS-DNA, and PNA. Methods to accomplish surface attachment include, but are not limited to, biotin-avidin chemistry, metal-affinity coordination, thiol bonding, hydrophobic interactions, and DNA-directed immobilization. Other means known in the art can be utilized. The

35   surface (30) can be a solid planar macromaterial or spherical or other shaped material, or a microscopic planar, spherical or other shaped micro- or nanomaterial, a nanocrystalline or modified nanocrystalline material, or a molecular or biomolecular assembly composed of protein, DNA, RNA, PNA, morpholino

DNA, or other biomolecule and their derivatives, molecularly templated materials, naturally occurring

polymers, minerals, and any similar base material. Those skilled in the art would understand that the

biosensor of the present invention could be made without the use of a surface (30) by tethering the

modular arm element (20) directly to the biorecognition element (10). The biorecognition element (10)

5   allows for specific oriented surface attachment (40), and contains a biorecognition module (50) that is

site specifically labeled with a signaling module (60). The types of biorecognition module (50) includes,

but is not limited to, proteins, such as enzymes, receptors, bPBPs, antibody fragments, and peptides),

aptamers, carbohydrates, DNA, PNA, and RNA. The modular arm (20) allows for specific oriented

surface attachment (40), and comprises a flexible arm (70) and a recognition module (80), and has been

10   site-specifically labeled with a signaling module (60). The flexible arm (70) is comprised of flexible

moieties, including, but not limited to, SS-DNA, DS-DNA, combinations of SS-DNA and DS-DNA,

thiolated DNA, RNA, thiolated RNA, linear homopolymers, linear copolymers, block copolymers, PNA,

α peptides, β peptides, protein, polymer, or oligosaccharide. The signaling module (60) includes, but is

not limited to, fluorescent dyes, quenchers, electrochemically active groups, quantum dots and enzymes.

15   The recognition module (80) includes, but is not limited to, antigens, epitopes, analytes, substrates,

proteins, peptides, toxins, sugars, biological agents, and analogs of said. The recognition module (80) is

attached to the distal end of the flexible arm (70). The binding of the recognition module (80) with the

biorecognition module (50) provides a biosensor that is in a ground state by bringing both signaling

modules (60) into close proximity to each other. This close proximity establishes a baseline fluorescence

20   resonancy energy transfer (FRET). Analyte added to the biosensor will competitively displace the

recognition module (80). Signal transduction of the FRET is sensitive to the displacement of the

recognition module (80). Binding affinity control can be achieved by, but is not limited to, stiffening of

the flexible arm (70), using different affinity biorecognition elements, or by temperature.

It would be understood by those skilled in the art that the biosensor of this invention could

25   be easily altered to detect a wide range of analytes of interest. Disclosed are the components and

architecture of a biosensor as well as a method of preparing and assembling a reagentless and reusable

biosensor with tunable differential analyte binding properties. This sensor consists of at least two

macromolecular entities that are able to interact with each other for sensing. Both entities can be tethered

to a surface.

30   FIG. 4a depicts a schematic view of a biosensor for maltose in its resting state. The

modular arm element (20) is bound to the biorecognition element, maltose binding protein (MBP), (10)

by the recognition module (80), an analyte analog, β-cyclodextrin (β-CD), of the analyte of interest,

maltose. The signaling elements (60) of the biorecognition element (10) and the modular arm element

(20) are in close proximity, establishing a baseline FRET. It is understood by those skilled in the art that

35   the close proximity for establishing FRET generally occurs in the range of about 1 to 10 nanometers.

FIG. 4b depicts the schematic view of the biosensor after the introduction of analyte,

maltose, (110) to the biosensor. The recognition element, β-CD, (80) has been displaced by the analyte

(110), causing the flexible arm module (20) to move with respect to the biorecognition element. This

causes the signaling element (60) of the biorecognition element, MPB, (10) and the signaling element

(60) of the modular arm element to move with respect to each other, causing a measurable change in

FRET. A detector would provide the means for providing the excitation light and detection means for

5   measuring the FRET levels. The biosensor (100) can be washed to remove the analyte (110),

regenerating the biosensor to the resting state of FIG 4a.

FIG. 5a depicts the schematic view of the TNT biosensor in its resting state. The modular

arm element (20) is bound to the biorecognition element, anti-TNT-scFv fragment (α-TNB), (10) by the

recognition module (80), an analyte analog, (TNB), of the analyte of interest (110), TNT. The signaling

10   elements (60) of the biorecognition element (10) and the modular arm element (20) are in close

proximity, establishing a baseline FRET.

FIG. 5b depicts the schematic view of the TNT sensor after the introduction of analyte,

TNT (110) to the biosensor. The recognition element, α-TNB, (80) has been displaced by the analyte

(110), causing the flexible arm module (20) to move with respect to the biorecognition element, α-TNB,

15   (10). This causes the signaling element (60) of the biorecognition element, α-TNB, (10) and the signaling

element (60) of the modular arm element to move with respect to each other, causing a measurable

change in FRET. A detector would provide the means for providing the excitation light and detection

means for measuring the FRET levels. The biosensor (100) can be washed to remove the analyte (110),

regenerating the biosensor to the resting state of FIG 4a.

20   FIG. 7 shows the effect of adding a modulator to the sensor that alters its binding

characteristics. The sensor was self-assembled with Modular arm P1 tethered using oligo Bio3 and

MBP95C QSY7 attached with Bio-X NTA. The resulting titration against maltose is show in the top

graph A. A variant of the sensor described above with the addition of modulator DNA is depicted in

bottom graph B. Useful sensing range is defined as the range from 10-90% fractional saturation.

25   In one embodiment of the invention, the biorecognition element consists of a specific

protein, i.e. maltose binding protein (MBP) that has been dye-labeled. The modular arm element consists

of an analyte analog (i.e. beta cyclodextrin), a signaling module (i.e. a cyanine dye), a flexible arm

module (i.e. synthetic oligomeric DNA), and an immobilization module (i.e. biotin). The component

modules of the modular arm element are chemically linked to each other in a linear fashion using

30   synthetic chemical methods. In the sensor, the biorecognition module and the modular arm element

recognize and bind with each other. Specifically, the protein saccharide binding site binds the

cyclodextrin, and as the two incorporated dyes in the assembled sensor are in close proximity to each

other, fluorescence resonance energy transfer (FRET) takes place and can be measured. Upon contact of

the assembled sensor with target analyte, e.g. maltose or other structurally related sugar, displacement or

35   replacement of the cyclodextrin from the dissacharide binding site of MBP occurs, causing the two

incorporated dyes to move in space relative to one another, which results in a change in FRET that can be

monitored.

Real or apparent binding constants or other relevant physical properties (linked to sensor sensitivity and/or dynamic range and/or chemical or thermal stability) of the biosensor can be altered by hybridizing DNA of different compositions and lengths to the flexible arm module, yielding control over sensing kinetics and thermodynamics. Additionally, variants of MBP with different intrinsic sugar

5   binding properties can be substituted at will as the biorecognition element of the sensor, which also allows adjustment and control of sensor performance.

Because the biorecognition module and modular arm module are tethered to a surface, the target analyte can repeatedly be washed away and the sensor regenerated to a resting state ready for another sensing event. The sensor can also function as a completely independent, continuously functional

10   monitor for an analyte in an environment where the concentration of the analyte can change over time, such as in a stream of flowing liquid, where a detector, i.e., a supply of exciting light and detector of optical signals are present. Furthermore, given the tethered design, protein receptors and analogs that may not normally bind together in solution can be forced to interact cooperatively for sensing events.

The sensing assembly is easily immobilized and assembled on microtiter well surfaces,

15   takes advantage of biological specificity, links target binding with signal generation, and functions in a reversible and regenerable manner. Controlled immobilization and orientation of proteins while maintaining their relevant activity on a solid surface remains challenging. To accomplish this, previous biosensor assemblies have been described that rely on hydrogel encapsulation of sensor components. The method of the present invention uses an approach that relies on self-assembly of components upon a

20   protein-passivated surface. The degree of structural and functional control afforded by this approach makes this general assembly method ideal for assembling a variety of receptors for sensing wide range of targets. Beginning with the concept of surface-tethering all sensor components, several key design features were considered. In order to immobilize and organize the required molecular elements, reliance on readily accessible and robust avidin-biotin assembly methodology was desirable, so the sensor was

25   assembled on NA-coated microtiter plate wells and monitored with a fluorescent microtiter plate reader, technology readily accessible or already present in many biological testing laboratories.

Methods utilized for surface confinement of both bioreceptor and analyte analog, maltose binding protein and β-CD in this case, needed to provide sufficient freedom of motion for displacement of the analyte analog by the target analyte during sensor operation. To accomplish this, a multifunctional

30   modular sensor arm was conceived that would be structurally flexible, yet incorporate the analyte analog, FRET donor dye, and surface-tethering element in a single chemically linked unit. A ternary B-CD-Cy3.5-DNA oligonucleotide tether arm that could be immobilized by DNA directed immobilization (DDI), yet easily made using commercially obtained materials, was selected to fill this role. Complementary base pairing specificity in DDI allowed a high degree of spatial control in sensor self-

35   assembly and placed the extended flexible tether arm onto the NA surface in an oriented fashion in close contact with the protein receptor. Similarly, oriented immobilization of His-tagged MBP bioreceptor variants was assured by using engineered versions of the protein that allowed single-point attachment to

7

the NA surface via biotin-X-NTA. As oligohistidine sequences are incorporated into many cloned and expressed proteins for metal affinity purification, many types of bioreceptors should be able to function in similarly constructed sensors after being labeled with an appropriate site-specific quencher dye.

Means for potentially modulating sensor performance were also considered and incorporated in the system. Sensors can easily accommodate 'switching in' of mutant receptor proteins as well as changes in the length or composition of DNA tethering elements to effect alteration of sensor performance.

There are several useful features of the present sensor design. The sensor can function with either of the two FRET dyes acting as energy donor or acceptor. Although only two dye pairs were used in the current work, the numerous FRET dye pairs available can provide the basis for the construction of multiple sensor versions, including an array or 'multiplex' sensing surfaces or devices. The present prototype sensor could be regenerated and re-titrated with maltose several times, yielding essentially the same binding constant with each subsequent titration. In its present configuration, 8 to 10 uses were possible before useful changes in fluorescence were eliminated, perhaps due to cumulative FRET dye photobleaching, MBP denaturation, or gradual dissociation of sensor components from the polystyrene surface during washing. However, the fact that the sensor assembly could be regenerated, re-used and yield essentially the same result is very encouraging.

Sensors based on this invention can be preassembled, dried, shipped, and reconstituted for use in the field. One advantage is the relatively small loss sensor performance due to tethering of all components to a surface. The effective concentrations of the surfaced-confined elements, present in approximately equimolar amounts, are undoubtedly very large, yet relatively low maltose concentrations were able to activate the sensor. The significant broadening of the binding curve for maltose, relative to the binding curve obtained for the components free in solution, indicates that a heterogeneous set of interactions between sensor components takes place on the surface. A subset of surface components have relatively optimal binding interactions between tethered β-CD and MBP so that they respond only to high concentrations of maltose. This subset is useful for sensing soluble sugar at high concentration, but is unresponsive to maltose at lower concentrations. Another surface-bound component subset forms interactions that are much less optimal for binding of the pendant β-CD of the DNA-dye-cyclic polysaccharide tethered arm within the MBP sugar binding site. In this case, maltose competes effectively for binding when present at much lower concentrations. Paradoxically, rather than being a liability for sensing, the effect of this surface heterogeneity is to expand the effective dynamic range of the system. In fact, this unexpectedly complex behavior functions to ameliorate the limited dynamic range that is a fundamental problem in most recognition-based sensing systems. Furthermore, greater control of sensor dynamic range can be accomplished by formation of even more complex surfaces, such as demonstrated here by use of alternate DNA tether arms with hybridized modulator DNA.

Progressive changes of the shape of the analyte binding curve over a relatively small temperature range above ambient (25 – 40 °C), leading to an endpoint at the upper temperature where

sensor response approaches ideal apparent two-state binding behavior suggests "melting away" of most or all of the low-energy surface interactions contributing to surface heterogeneity. Initial heterogeneity of the complex sensor surface leading to the observed behavior could result from a wide variety of molecular interactions. Inter- or intramolecular DNA, DNA-protein (with MBP and/or neutravidin),

5   and/or interactions of any or all of the components with the substrate polystyrene surface could play a role. Most likely, a complex synergistic interplay among the sensor elements due to the above interactions leads to the observed behavior. Predictable control and optimization of sensor surface behavior is a goal for future efforts, in which additional systematic alterations of sensor component properties (such as very careful design of DNA components to eliminate possible low-melting

10   intramolecular hairpin formation) needs to be carried out. Nonetheless, even in the absence of extensive optimization of the materials employed, the sensor surfaces we have constructed are able to function as sensors, and function repeatedly, which suggests that the overall assembly strategy employed is quite robust.

The modulation of sensor behavior achieved by changing the structure and composition of

15   the synthetic DNA used in the modular tether arm demonstrates a way of fine tuning the sensors of the present. While recently reported work demonstrated irreversible off-to-on switching by annealing of complementary DNA to an engineered enzyme-containing assembly, the present sensor design is the first to make use of DNA-DNA interactions to modulate the binding properties of a fully reversible biosensor assembly. When DNA is used for tethering and modulation purposes in similar designs, secondary

20   structure considerations must be carefully examined. Furthermore, although examples disclosed have used DNA for the tethering and modulation functions of the biosensor, a wide range of other materials are feasible for sensor arm construction, including PNAs, peptides, and other linear oligomeric or polymeric materials. Similarly, non-protein receptors such as DNA or RNA aptamers, templated surfaces, or other types of molecular receptors can function as recognition elements. Although

25   quenching of organic dyes for biosensor signal generation was used in the examples herein, use of optical components such as quantum dot energy donors, or altogether different read-out modalities, such as enzymatic or electrochemical monitoring, are also possible.

The foregoing example exemplifies only one biosensor assembly that can be prepared using the architecture, components and methodology described in the invention. Using different

30   components, but using the same or similar basic architecture and assembly methods, a very large number of sensors, each having the novel features described, may be prepared.

Having described the invention, the following example is given to illustrate specific applications of the invention, including the best mode now known to perform the invention. These specific examples are not intended to limit the scope of the invention described in this application.

35   Example 1: Biosensor for Maltose:

Maltose Binding Protein. In this assembly, the bio-recognition elements employed are engineered variants of E. coli maltose binding protein (MBP). MBP, a well-characterized member of the

bPBP superfamily, has been used extensively for prototyping purposes in the previously described
biosensors, as well as in redox- and quantum dot-based hybrid FRET biosensors. Binding of maltose to
MBP is accompanied by a conformational change; however, the FRET-based biosensor does not depend
on a change in conformation for signal generation.

5   As illustrated in FIG. 4a, Quencher-dye (60) labeled biotinylated *E. coli* maltose binding
protein (MBP) (10) bound in a specific orientation to a NeutrAvidin-coated surface (30) is employed as a
biorecognition element (10). To complete sensor formation, a flexible arm module (20) comprised of a
flexible biotinylated DNA oligonucleotides (115), a fluorescence resonance energy transfer (FRET)
donor dye (60), and a distal β-cyclodextrin (β-CD) analyte analog (80) is bound in an equimolar amount

10   to the same surface by means of DNA directed immobilization. After self-assembly, a baseline level of
FRET quenching is observed due to specific interaction between the β-CD of the flexible tether arm and
the sugar binding site of MBP, which brings the 2 dyes into close proximity. Addition of the target
analyte, maltose, displaces the linked β-CD-dye of the DNA-based tether arm, and a concentration
dependent change in FRET results. Biosensor sensitivity and dynamic range can be controlled by either

15   using MBP variants having different binding constants or by binding of modulator DNA oligonucleotides
that are complementary to the flexible DNA tether

The biosensor is self-assembled on a NeutrAvidin^{TM} (NA)-coated surface, and the basic
sensing unit consists of an MBP bio-recognition element that binds the cyclic sugar β-cyclodextrin (β-
CD) that is co-immobilized on the same surface as part of a multifunctional modular "tether arm." The

20   distal β-CD element of this modular tether arm is linked to an integrated dye molecule that functions in
signal generation. The target analog and signal transduction functionalities (β-CD and dye) in the same
module are anchored to the sensor surface by hybridized DNA interactions via DNA-directed
immobilization (DDI) utilizing modified oligonucleotides. Following biosensor assembly, an appropriate
sugar analyte (e.g. maltose) can compete with β-CD for binding at the MBP binding site.

25   Movement of the β-CD analyte-analog into or out of the protein binding site is coupled
with obligatory movement of the integrated signaling dye, and this spatial displacement forms the basis
for quantitative reporting of analyte sugar concentration by changes in FRET. The present biosensor,
which is composed of molecular components that exist in direct spatial contact, and that is functional in a
quantitative, continuous, and reversible manner that requires no additional or secondary reagents meets

30   the rigorous criteria that define a biosensor.

MBP95C, MBP80C and MBP-AT (containing the specific AviTag recognition sequence
for in vivo biotinylation) were engineered and expressed as described below. The DNA coding sequence
for MBP protein ($Mr \sim 44$kD) is contained on a standard multicopy plasmid vector containing the
ampicillin resistance gene and was expressed. This MBP gene sequence was engineered to express a C-

35   terminal 5 histidine sequence along with aspartate 95 or threonine 80 changed to cysteine (MBP95C,
MBP80C) using standard gene assembly and cloning techniques. To create an MBP that expresses the

AviTag specific biotinylation sequence, a MBP mutant plasmid was engineered with codons changed to those recognized by *Xho*I and *Hind*III 27-30 and 15-18 bps, respectively, from the C-terminal penta-histidine coding sequence. The plasmid was then digested with *Xho*I and *Hind*III and oligonucleotides for a modified AviTag sequence ligated into these sites which coded for the sequence:

5   AGLGGLNDIFEAQKIEWHE. *In vivo*, biotin is covalently attached to the lysine, K, residue in this sequence. Transformants were screened and sequenced for correct integration. This MBP-AT (AviTag) plasmid was co-transformed into *E. coli* strain AVB99 along with pACYC184 (Avidity, Denver CO), which expresses the biotin holoenzyme synthetase BirA. Cells were grown overnight in 100 ug/mL ampicillin/10 ug/mL chloramphenical media and induced with isopropyl β–D-1-thiogalactopyranoside

IleAsnGlyAspLysGlyTyrAsnGlyLeuAlaGluValGlyLysLysPheGluLysAsp   31
ThrGlyIleLysValThrValGluHisProAspLysLeuGluGluLysPheProGlnVal   51
AlaAlaThrGlyAspGlyProAspIleIlePheTrpAlaHisAspArgPheGlyGlyTyr   71
AlaGlnSerGlyLeuLeuAlaGluIleThrProAspLysAlaPheGlnAspLysLeuTyr   91
                                80
ProPheThrTrpAspAlaValArgTyrAsnGlyLysLeuIleAlaTyrProIleAlaVal   111
                95
GluAlaLeuSerLeuIleTyrAsnLysAspLeuLeuProAsnProProLysThrTrpGlu   131
GluIleProAlaLeuAspLysGluLeuLysAlaLysGlyLysSerAlaLeuMetPheAsn   151
LeuGlnGluProTyrPheThrTrpProLeuIleAlaAlaAspGlyGlyTyrAlaPheLys   171
TyrGluAsnGlyLysTyrAspIleLysAspValGlyValAspAsnAlaGlyAlaLysAla   191
GlyLeuThrPheLeuValAspLeuIleLysAsnLysHisMetAsnAlaAspThrAspTyr   211
SerIleAlaGluAlaAlaPheAsnLysGlyGluThrAlaMetThrIleAsnGlyProTrp   231
AlaTrpSerAsnIleAspThrSerLysValAsnTyrGlyValThrValLeuProThrPhe   251
LysGlyGlnProSerLysProPheValGlyValLeuSerAlaGlyIleAsnAlaAlaSer   271
ProAsnLysGluLeuAlaLysGluPheLeuGluAsnTyrLeuLeuThrAspGluGlyLeu   291
GluAlaValAsnLysAspLysProLeuGlyAlaValAlaLeuLysSerTyrGluGluGlu   311
LeuAlaLysAspProArgIleAlaAlaThrMetGluAsnAlaGlnLysGlyGluIleMet   331
ProAsnIleProGlnMetSerAlaPheTrpTyrAlaValArgThrAlaValIleAsnAla   351
AlaSerGlyArgGlnThrValAspGluAlaLeuLysAspAlaGlnThrLysLeuThrLys   371
                                 / *Xho*I /   /*Hind*III/
GlySerHisHisHisHisHis...   ---378

*(IPTG) and 50 μM d-biotin. MBP-AT was purified and biotinylated MBP-AT was further purified using the Immuno*Pur

e Immobilized Monomeric Avidin Kit (Pierce, Rockford Ill). The MBP sequence with locations of 80C and 95C highlighted is below. Position of codons changed to *Xho*I and *Hind*III also shown.

35   Mutant proteins were specifically labeled on cysteine residues using maleimide activated

Cy3 dye (extinction coefficient 150,000 $M^{-1}cm^{-1}$, quantum yield >0.15, Amersham Biosciences,

Piscataway NJ) or QSY 7 dye (extinction coefficient 90,000 M cm , Molecular Probes, Eugene OR).

β-CD-Cy3.5-P1 DNA Synthesis and Mass Spectral Analysis: Bifunctional NHS-ester

activated Cy3.5 dye (extinction coefficient 150,000 M cm , quantum yield >0.15, Amersham

Biosciences) solubilized in 0.136M Na tetraborate buffer pH 8.5 was added to a vial containing ~5

5   nanomoles amino-functionalized P1 DNA. After reacting for 20 min at room temperature in the dark, a

100-fold excess of monoamino-beta-cyclodextrin was added. After 4 hrs, 200 µL of HE buffer (10 mM

HEPES, 1 mM EDTA, pH 7.0) was added and the product precipitated with 25 µL - 3M NaCl and 650

uL cold ETOH at -20°C. The precipitate collected by centrifugation was washed 4 times with ETOH and

dried in a vacuum centrifuge. Dried pellets were solubilized in HE buffer and synthetic products

10   separated from underivatized dye on 12% acrylamide gels by electrophoresis. Product band(s) were

excised and the β-CD-dye-DNA adduct (abbreviated as P1) eluted by passive diffusion into HE buffer.

Adduct(s) were concentrated/desalted using an oligonucleotide purification cartridge, OPC. Pure

products were subjected to mass spectral analysis. Samples were de-salted and removed from non-

volatile buffer(s) by solid phase extraction using C18 zip tips. Samples were bound to the tip and washed

15   3x with high purity water, 0.1% trifluoroacetic acid (TFA). Samples were subsequently eluted with 10 µL

of 75% acetonitrile (ACN), 0.1% TFA, added to 90 µL of MALDI matrix (35 mg/ml 3-hydroxypicolinic

acid in 30% ACN, 10 uL of 50 mg/ml ammonium citrate). One µL of each solution was deposited onto

the MALDI plate. Samples were analyzed by MALDI-TOF mass spectrometry using a Voyager-DE

PRO. Using the negative ion and linear TOF modes, signal was detected for the ternary product

20   consisting of cyclodextrin-Cy3.5 dye-P1 DNA at m/z 7068. The mass calculated for the cyclodextrin-

Cy3.5 dye-P1 amine DNA complex (P1) was 7073 amu. The synthetic product consisting of P1 DNA-

Cy3.5 dye (without appended β-CD) was similarly isolated and identified.

Sensor Assembly: Reacti-Bind Neutravidin (NA) Coated Plates or opaque white microtiter

plates coated with NA were prepared. For each microtiter well, 7-10 picomoles of P1 were allowed to

25   hybridize to the same amount of complementary biotinylated attachment DNA (Bio1,2,3) in Tris-EDTA

buffer pH 8 (TE). Modulator DNA was added where indicated in 2-fold concentration. The DNA

containing solutions were heated to 80°C for 5 minutes and then cooled slowly to room temperature to

preclude any possible secondary structure formation. This solution was then diluted into 50 µL PBS and

added to each NA microtiter well for 1 hour of binding at RT. Wells were washed with 200 µL PBS and

30   10 picomoles of biotinylated-MBP-AT95C-Cy3 added to each well in 50 µL PBS where indicated.

Alternatively, 50-80 picomoles of MBP95C-QSY7 or MBP80C-QSY7 was preincubated with an

equimolar amount of biotin-X nitrilotriacetic acid tripotassium salt (Biotin-X NTA, Biotium, Hayward

CA) for 2 hrs at room temperature and added in 50 µL PBS to wells containing P1. The final, mixed

sensor was allowed to bind and self assemble for 1 hr at room temperature, washed with 200 µL PBS and

35   equilibrated in 50 µL PBS for 15 min before addition of sugar for testing. Sensors were regenerated by

washing with 20 volumes of buffer and allowing the sensor to re-equilibrate for 20 min to 1 hr in 50 µL

PBS. The table below lists oligonucleotides sequences referenced.

Name	# of nucleotides	Sequence 5'-3'	TM °C
P1	16	NH$_2$-C$_6$-ATACCGTTCGCGCCCG	61.8
Bio1	24	Bi-C$_{15}$-ACTGACTGCGGGCGCGAACGGTAT	69.7
Bio2	34	Bi-C$_{15}$-ACTGACTGGAATCTGAATCGGGCGCGAACGGTAT	71.9
Bio3	44	Bi-C$_{15}$-ACTGACTGTACGAGTTGAGAATCTGAATCGGGCGCGAACGGTAT	74.0
Mod1	15	GATTCTCAACTCGTA	48.0
Mod2	20	ATTCAGATTCTCAACTCGTA	54.3

NH$_2$ - Amine
C$_6$ - 6-carbon spacer
C$_{15}$ - 15-carbon spacer
Bi – Biotin
Highlighted area where modulator DNA Mod1 and Mod2 hybridize

           <u>Fluorometry and Titration</u>: Fluorometric analysis of microtiter well plates was performed on a Safire Dual Monochromator Multifunction Microtiter Plate Reader. For the Cy3-Cy3.5

5   fluorophores, samples were excited at 520 nm and emission collected at 605 nm. Excitation at 550 nm and 600 nm emission were used for the QSY 7-Cy3.5 pair. For titrations, 5 µL of each appropriate sugar solution was added and mixed at RT for 5 min as described. Background fluorescence was subtracted and data normalized for volumetric changes. Data was transformed using a Hill 4-parameter plot and approximate binding constants, K$_{app}$, estimated in these conditions of multiple equilibria along with

10   useful sensing ranges using SigmaPlot. For all titrations, the Hill coefficient approached 1, indicating a 1:1 maltose/MBP interaction.

           <u>Sensor Self-Assembly and Testing:</u> Organized self-assembly of both the dye-labeled MBP receptor and extended modular arm bearing the β-CD analyte analog and reporter dye occurs on NA coated microtiter plates. It is possible to assemble the sensor components either by mixing equimolar

15   amounts of the dye-labeled biotin-functionalized MBP and β-CD-Cy3.5-P1DNA/Bio1,2,3 modular tether arm in solution before attachment to the NA surface or by allowing the separate components to bind separately and sequentially. If the separate components bind separately and sequentially, empirically determine the amount of first component bound to the surface to leave enough remaining accessible biotin-binding sites for filling in with the second sensor component.

20   The NA biotin binding sites on the surface are ~50% occupied by a biotin-X-NTA linker coordinated to MBP through a C-terminal pentahistidine extension. Depending on the sensor variation, the remainder of the biotin binding sites are occupied by single-stranded DNA oligomers of varying lengths (termed Bio1, Bio2, or Bio3 of 24, 34, 44 bases in length, respectively). Each surface-bound oligo being linked to the surface through a flexible 5' hydrophilic 15- atom biotinylated TEG

25   (triethethyleneglycol) linker on one end and hybridized to β-CD-Cy3.5-P1DNA on the other. Thus, in the completely assembled sensor, the β-CD-FRET dye modules critical for sensing are held on the surface in

close molecular proximity with bound MBP to form active sensing complexes.

On the fully assembled sensor surface, an equilibrium is established in which immobilized MBP is positioned to bind the pendant β-CD of the modular arm element within its sugar binding site. With this binding event, the FRET dye pair is simultaneously brought into position for a baseline level of

5   fluorescence quenching to occur. Due to the relatively small size of the MBP molecule and favorable Förster R0 values for the dyes used, energy transfer between a fluorophore located at the binding site of MBP and a dye label placed virtually anywhere on the protein is highly efficient.

Native MBP binds both the disaccharide maltose (KD of 0.9 µM), and β-CD (KD of 1.8 µM) with similar affinities. In the biosensor, signal generation is designed to occur when added maltose

10   competitively displaces β-CD from the MBP sugar binding site. An increasing degree of occupancy of the binding site by an increasing concentration of maltose, concomitant with decreasing binding site occupancy of the tethered β-CD, is coupled quantitatively with changes in FRET occurring between incorporated system dyes, forming the basis for sensor function. The sensor assembly is designed to be re-set to a baseline quenching state by simply removing maltose by washing/dilution, so that quantitative

15   sensing can be carried out repeatedly. Alternatively, when assembled in a properly configured flow cell or fixed within a bioreactor, a derivative of this molecular sensor assembly may be able to continuously and reversibly monitor fluctuations in maltose concentration.

Below is the structure of the three part tetherable modular arm and the relevant absorption.

20
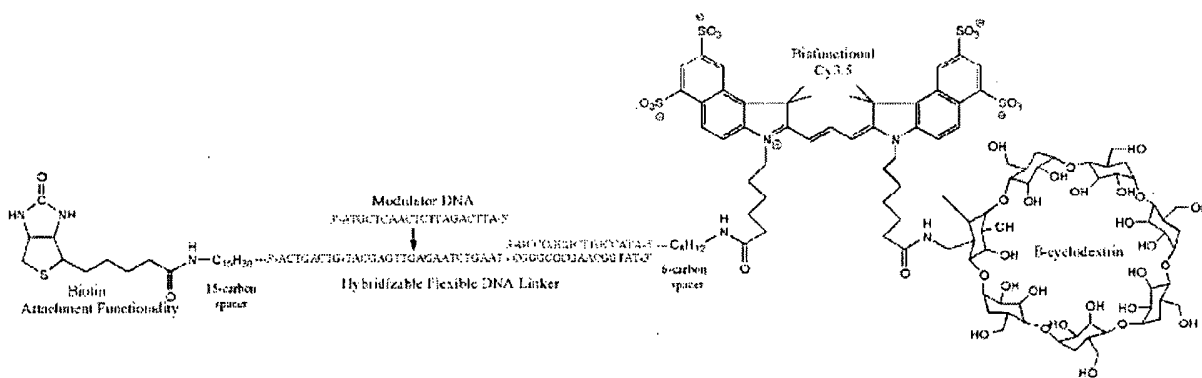
In this configuration, MBP was labeled at either of two engineered residues (80C or 95C) by thiol-reactive QSY 7, a dark (non-emitting) quencher dye. β-CD-Cy3.5-P1DNA was bound to the surface via the 34 nucleotide Bio2 oligo and MBP95C-QSY7 was surface localized via biotin-X-NTA. In the initial state of the sensor (no maltose), proximity of the Cy3.5 donor dye of the tethered arm to MBP-

25   bound QSY 7 acceptor dye resulted in partial quenching of Cy3.5 fluorescence. Emission of the Cy3.5 increased upon addition of maltose, strongly suggesting that competition for the MBP sugar binding site occurs between the soluble disaccharide and the β-CD moiety of the β-CD-Cy3.5-P1DNA modular arm. A change in average FRET quenching efficiency occurred due to a net difference in dye-dye

distance/orientation in the system. The binding curve obtained was a smooth function of maltose concentration, but was relatively broad in the concentration dimension compared with titrations using soluble components (see below) suggesting that physical constraints related to tethering lead to inhomogeneity in the binding and signal generating apparatus. Nonetheless, the assembly performed

5   effectively in sensing maltose.

After saturation with maltose, the sugar could be removed and the sensor reset to its baseline quenching value by rinsing the surface with buffer. Titration could then be carried out with essentially identical results, followed by repeated rounds of regeneration and sensing. The K_{app} derived for maltose binding to this sensor was 6.7 ± 0.7 μM. Control experiments were performed in which the β-

10   CD-Cy3.5-DNA modular sensing arm was replaced with a partial sensing arm consisting of Cy3.5-P1DNA without the β-CD target analog recognition element. Titration of this control sensor assembly with maltose gave essentially no change in emission spectra or fluorescence intensity, demonstrating that function of the sensor depended on recognition of the β-CD moiety by MBP. Replacement of MBP with a non-functional protein (apo-myoglobin bearing a C-terminal hexahistine) also resulted in no change in

15   baseline emission with added maltose. The fluorescence does drop with regeneration, suggesting an upper limit to the number of regenerations even though essentially the same binding constant is derived with subsequent titrations.

Fluorescence changes during titration with maltose were also monitored with the same components present both in solution phase and in a "half-tethered" configuration. Starting with an

20   equilibrium-state solution of 500 nM MBP95C QSY7 and 50 nM β-CD-Cy3.5-P1DNA, systematic changes in quenching that occurred due to competitive displacement of β-CD by maltose yielded a K_{app} of 1.9 ± 0.7 μM. Under these relatively dilute conditions, chosen to avoid inner filter effects, the β-CD containing reagent would be expected to occupy about 5 – 10% of the available binding sites of the MBP95C QSY7 present at equilibrium. The ~5% fluorescence change that occurred at maltose

25   saturation was consistent with essentially complete displacement of the β-CD-Cy3.5-P1DNA. The binding curve for the soluble system was more compressed on the concentration axis compared to the binding curve of the fully tethered sensor, reflecting more ideal titration behavior for components freely diffusing in solution, and the K_{app} value obtained from the binding data are consistent with previous MBP solution phase titrations.

30   In another titration, MBP95C QSY7 was present in solution at 40 nM, while β-CD-Cy3.5-P1DNA was tethered to the NA surface via DDI with biotinylated oligonucleotide Bio2. A K_{app} for maltose binding of 6.0 ± 0.6 μM was determined and the shape of the binding curve indicated retention of the essentially ideal binding behavior observed for the fully soluble system; thus, the cyclic sugar of surface-tethered β-CD-Cy3.5-P1DNA appeared to be presented to the soluble protein receptor in an

35   essentially homogenous manner, unlike the fully tethered sensor assembly where geometric constraints leading to surface inhomogeneity are likely responsible for the broadened binding curve observed.

The behavior of the biosensor has only minimal dependence on the length of this tethering segment over the ranges investigated. Immobilization segments Bio1, Bio2, or Bio3 DNA of 24, 34, or 44 bases in length, respectively, were tested. The table below illustrates the sensor properties.

5   Using an estimated value of 3.4Å for each base in a fully extended ssDNA linker, these

Sensor Protein[1]	Functional Arm	Arm Attachment	Modulator	K_{app} μM	Estimated useful sensing range[2]	% Fl increase upon sensor saturation[3]	Comment
MBP95C	P1	NA	NA	1.9 ± 0.7	350nM-6μM	5	Both components in solution
MBP95C	P1	Bio2	NA	6.0 ± 0.6	2.5μM-10μM	6	Only P1 tethered via Bio2
MBP95C	P1	Bio2	NA	6.7 ± 0.7	1μM-50μM	10	P1 tethered via Bio2 & MBP95C tethered via Bio-X NTA
MBP95C	P1	Bio3	1	4.0 ± 0.6	50nM-650μM	7	Modulator present
MBP95C	P1	Bio3	2	11.3 ± 1.9	10nM-1mM	9	Modulator present
MBP95C	P1	Bio1	NA	3.0 ± 0.3	1μM-90μM	10	
MBP95C	P1	Bio3	NA	4.8 ± 0.3	500nM-30μM	12	
MBP80C	P1	Bio3	NA	575 ± 15	10μM-5mM	133	
MBP80C	P1	Bio3	2	404 ± 10	7μM-5mM	127	Modulator present
MBP80C	P1	Bio3	2	375 ± 25	3μM-3mM	36	See below[4]
MBP95C/MBP80C	P1	Bio3	NA	153 ± 27	4μM-8mM	86	Composite sensor
MBP-AT95C	P1	Bio3	NA	10.5 ± 1.4	1μM-150μM	6	Biotinylated MBP-AviTag
MBP-AT95C	P1	Bio3	2	9.3 ± 1.3	500nM-100μM	5	Biotinylated MBP-AviTag

NA – Not applicable. AT – AviTag. All readings are performed at 20-22 °C See Suppl. for oligonucleotide sequences and Fig 1 for schematic
[1]Unless otherwise noted, the protein is tethered to the neutravidin surface via the 5-histidine sequence using Ni-X NTA as in Methods
[2]This is the estimated concentration range for which these sensors can be used usefully and is defined as the range between 10% and 90% saturation.[ref 15,17]
[3]Calculated as $(Fl_{sat}-Fl_0)/Fl_0 \times 100$ where Fl_{sat} = fluorescence at saturation and Fl_0 = fluorescence before the addition of sugar
[4]Plate with sensors in wells titrated 4 times consecutively, air dried and stored for 2 weeks in refrigerator and then titrated 3 times consecutively

linkers varied from ~82 to ~150 Å in potential length of the single-stranded segment. Binding constants obtained for these sensor variations remained in the low micromolar range, varying no more than ~ 2-fold, 6.7 ± 0.7 μM for Bio2 versus 3.0 ± 0.3 μM for Bio1. The behavior of the system assembled with Bio3, the longest tethering element, was similar to that for Bio1. The shape of the binding curve was

10   similar in each case, and the net change in fluorescence between maltose-free and maltose-saturated states for each of the three variations tested was ~10%, demonstrating that the degree of functional surface coverage was not dependent on the ssDNA tether length. The behavior of the biosensor has only minimal dependence on the length of this tethering segment over the ranges investigated.

Modulation of Binding Affinity and Useful Sensing Range   Effective means to modulate

15   the sensitivity and/or dynamic range of the biosensor were sought. The first way explored for controlling sensor behavior involved relatively straightforward substitution of an MBP variant with altered sugar binding properties. A second variation on this form of control involved formation of a "mixed" composite sensor consisting of two sugar receptor variants on the same surface having different maltose binding profiles. A third level of sensor control involved hybridization of "modulator" DNA strands to

20   the residual single-stranded section of the β-CD-Cy3.5-P1DNA/Bio3 tether arm in an attempt to alter the extension or stiffness of the tether arm by altering the ratio of ss/ds DNA in this modular component.

As a first level of control, QSY 7-labeled MBP variant MBP80C having significantly different maltose binding characteristics from QSY 7-labeled MBP95C was used as the bioreceptor in

order to modulate sensitivity and dynamic range. In this MBP variant, labeling at engineered cysteine-80 with the reporter dye significantly increases its K_{app}. Solution phase titration of Cy3-labeled MBP80C under similar conditions yielded a maltose KD of 70 μM. FIG. 8, in the graph labeled A, shows the binding curve from maltose titration of a sensor consisting of the β-CD-Cy3.5-P1DNA modular arm

5   tethered with Bio3 and assembled with MBP95C QSY7, while FIG. 8, in the graph labeled B, shows data for the sensor constructed with MBP80C QSY7. The K_{app}'s and useful sensing ranges for the different sensor configurations are 4.8 ± 0.03 μM/500 nM -30 μM and 575 ± 15 μM/10 μM -5 mM, where useful sensing range was estimated from 10 and 90% sensor response to maltose. From these results it was clear that facile tuning of sensor sensitivity and dynamic range can be accomplished by

10   altering receptor affinity. Combining receptor variants which have differing binding properties into a composite biosensor is one approach to creating biosensors with changed dynamic ranges.   FIG. 8, in the graph labeled C, presents the results from maltose titration of a composite sensor assembled with equimolar proportions of MBP95C QSY 7 and MBP80C QSY7 receptors on the surface. Using this sensor assembly, there was a significant shift in K_{app} (153 ± 27 μM) and useful sensing range of ~ 4 μM -

15   8 mM vs. 4.8 ± 0.3 μM and 575 ± 15 μM for the MBP95C QSY 7 and MBP80C QSY7 sensors, respectively. Not surprisingly, because of the significantly different intrinsic ΔF values for the two base sensor configurations, composite sensor properties were largely dominated by MBP80C QSY7 binding and signaling. By more closely matching net ΔF values of the constituent receptor components or adjusting ratios of each constituent sensor in the composite, finer control of sensor function could likely

20   be achieved. Combinatorial screening methods could also be effective in optimizing composite sensors.

A third means to control sensor performance is modification of sensor properties by altering the extension or stiffness of the tether arm by changing the ratio of ss/ds DNA in β-CD-Cy3.5-P1DNA modular component was explored. Hybridizing complementary DNA to the tether arm will change a significant portion of the DNA in the tether arm from single-stranded (ss) to a more rigid

25   double-stranded (ds) DNA form, and the resultant changes in rigidity of the DNA linker arm might allow control of sensor performance. The β-CD-Cy3.5-P1DNA/Bio3/Modulator DNA tether arm was self-assembled using DNA annealing by slow-cooling the combined heat denatured components (Temperature for all dsDNA- hybrids in the sensor was designed to be > 65°C) prior to room temperature immobilization on the NA surface along with MBP95C QSY 7. In the "unmodulated" β-CD-

30   Cy3.5-P1DNA/Bio3 arm, only 16 of the available 44 bases in the Bio3 oligonucleotide (~35%) were involved in DNA duplex interactions. Hybridizing complementary MOD1 or MOD2 DNA to Bio3 in the β-CD-Cy3.5-P1DNA/Bio3 complex raises this number to 31/44 bases (~70%) or 36/44 bases (~82%), respectively. FIG. 8, in the graphs labeled D and E, show binding curves obtained from maltose titration of the MBP95C QSY 7 sensor with MOD1 or MOD2 oligonucleotides hybridized to their complements

35   within the β-CD-Cy3.5-P1DNA/Bio3 modular assembly. The shapes of the binding curves for the modulated assemblies differ considerably from the binding curve of the unmodulated sensor, and different K_{app} values and useful sensing ranges for the modulated assemblies are observed. Specifically,

the binding curves for the oligonucleotide modified sensors are broader and shallower than that of the parent sensor, and the useful sensing ranges are correspondingly greater, ranging from 500 nM-30 μM for the unmodified sensor to 50 nM-650 μM for MOD1 and 10 nM-1mM for MOD2 containing MBP95C QSY 7 sensors. Similar experiments utilizing MBP80C QSY7 resulted in small changes in

5   K_{app}, but in this case the presence of modulator DNA did not significantly alter the useful sensing range. Changes in the packing of surface components due to the presence of modulator DNA could alter the binding behavior of MBP. Additionally, MBP is known to be very sensitive to small structural changes even distal from the binding site, which can significantly alter affinity. Clearly, this means of fine-tuning sensor properties can be successfully implemented, but at present the more direct methods previously

10   described are more predictable and robust ways to modulate sensor function.

            Stability of the immobilized sensor assemblies. Sensors assembled using MBP80C QSY7 and β-CD-Cy3.5-P1DNA/Bio3/MOD2 components were titrated with maltose in microtiter plate wells, purged of maltose by washing/dilution, then dried and stored at 4°C for 2 weeks to determine long term stability and regenerability of the sensors. Following rehydration with PBS, successful maltose titration

15   was carried out three times with regeneration. The K_{app} of 375 ± 25μM obtained from the sensor attached to the dry-stored plate was identical, within error, to that of the initially tested sensor.

            Sensor System Bioenergetics and Specificity. Maltose titration behavior was examined over a range of temperatures. Increasing concentrations of maltose were added to wells of a microtiter plate containing identical sensor assemblies based on MBP80C QSY 7 and β-CD-Cy3.5-P1DNA/Bio3.

20   After equilibrating and reading the plate at 25°C, the plate was re-equilibrated at 30°C and the fluorescence read with the same at 35 and 40°C. Of particular interest was the systematic change in the shape of the binding curve with temperature, from a broader binding isotherm at 25°C to a more steeply rising curve at 40°C, suggesting that with increasing temperature the range of functional configurations of the tethered components becomes smaller, resulting in more ideal binding behavior at higher

25   temperature. Sensor function is thus significantly temperature dependent. However, the temperature dependence of the shape of the binding curves makes it impossible to derive meaningful thermodynamic parameters in this complex system of multiple equilibria (e.g. Vant Hoff plots are likely to lack quantitative meaning). It is likely that sensor binding thermodynamics and kinetics would be affected by changes in other physical parameters such as pH, ionic strength and viscosity.

30   The ability of these surface-tethered maltose sensors to discriminate among different types of sugars was investigated by carrying out titrations with a range of sugars, including D-arabinose, D-galactose, D-glucose, lactose (an epimer of maltose), sucrose and β-CD, with maltose serving as the comparative standard. The table below illustrated sensor sensitivity to different sugars.

35

P1-Bio3-MBP95C-QSY7-Bio-X NTA

Sugar	D-Arabinose	β-Cyclodextrin	D-Galactose	D-Glucose	Lactose	Maltose	Sucrose	H2O
Type[1]	Mono	Oligo (7-monomers)	Mono	Mono	Di	Di	Di	NA
Oligosaccharide Linkage	NA	α-1,4 glucosidic	NA	NA	1,4-α glucosidic	α-1,4 glucosidic	α-1, β-2 glucosidic	NA
Δ FL[2] 100 nM	< 1%	14%	< 1%	< 1%	< 1%	100%	< 1%	< 1%
Δ FL[2] 1 mM	< 1%	58%	< 1%	< 1%	< 1%	100%	< 1%	< 1%

P1-Bio3-MOD2-MBP95C-QSY7-Bio-X NTA

Sugar	D-Arabinose	β-Cyclodextrin	D-Galactose	D-Glucose	Lactose	Maltose	Sucrose	H2O
Type[1]	Mono	Oligo (7-monomers)	Mono	Mono	Di	Di	Di	NA
Oligosaccharide Linkage	NA	α-1,4 glucosidic	NA	NA	1,4-α glucosidic	α-1,4 glucosidic	α-1, β-2 glucosidic	NA
Δ FL[2] 100 nM	< 1%	28%	< 1%	< 1%	< 1%	60%	< 1%	< 1%
Δ FL[2] 1 mM	< 1%	73%	< 1%	< 1%	< 1%	100%	< 1%	< 1%

[1]Mono, Di and Oligo – saccharide

[2]Δ FL = Percentage increase in PL intensity with respect to the initial value of the nanosensor, upon addition of the indicated amount of sugar, the response to 1mM maltose defines the 100% comparison response

NA-Not applicable

With sensors composed of either β-CD-Cy3.5-P1DNA/Bio3 or β-CD-Cy3.5-P1DNA/Bio3/MOD2 and MBP95C-QSY 7, the only non-zero response obtained, excepting maltose was for β-CD. The binding specificity of MBP is fully retained on the

5   sensor surfaces prepared.

Biotinylated MBP- AviTag Sensor Variant: Oriented attachment of the dye-labeled MBP to the NA surface for sensor construction has been accomplished in two different ways. The first method uses the heterobifunctional crosslinker Bio-X-NTA (where Bio is biotin, X represents an amino-methoxy spacer, and NTA stands for the nitrilotriacetic acid chelator functionality) to link C-terminally His-tagged

10   MPB variants to the surface NA. Another MBP variation, MBPAT-95C, was also employed in sensor assembly. In this protein, an AviTag biotinylation recognition peptide was genetically fused to the C-terminus of the MBP sequence. The AviTag sequence allows specific *in vivo* biotinylation by the biotin holoenzyme synthetase BirA and subsequent isolation of site-specifically biotinylated proteins directly from *E. coli* lysates. MBPAT-95C was created to investigate whether MBP biotinylated *in vivo* could be

15   used for attachment to the NA surface, thus eliminating the need for use of Bio-X-NTA or other potentially non-specific chemical biotinylation steps. Cy3-labeled MBPAT-95C was used to construct and test a Cy3-Cy3.5 emissive variant, where the Cy3.5 dye of β-CD-Cy3.5-P1DNA acts as an emissive

FRET acceptor. The K_{app} for maltose binding of 10.5 ± 1.4 was similar to the value derived from MBP immobilized using Bio-X-NTA. Cy3-labeled MBPAT-95C functions well as the receptor,

20   even though it is tethered to the surface by the biotinylated lysine of the 19-residue C-terminal AviTag peptide. Use of modulator DNA did not significantly alter sensor function. *In vivo* biotinylation of receptors thus represents another facile means to create components for use in sensor self-assembly. Successful use of this alternate receptor immobilization method implies that flexibility exists in the assembly strategy described herein.

25   Example 2 - TNT Biosensor: The self-assembled modular sensing strategy can be applied to the detection of an analyte completely unrelated to maltose, namely, 2,4,6-trinitrotoluene (TNT), by

altering two modules of the sensor assembly. Using the same sensor platform, a dye-labeled anti-TNT single-chain Fv antibody fragment (R-TNTscFv) was substituted for the MBP bioreceptor portion of the sensor and the multifunctional tether arm was modified to contain a dye attached to a modified internal base. The DNA arm is further modified to terminate with the TNT analogue 1,3,5-trinitrobenzene (TNB).

5   FIGS. 5a and 5b schematically depict the TNT sensor. The R-TNTscFv portion is allowed to bind the TNB analogue, bringing both dyes into proximity, establishing a baseline level of FRET, and this complex is then self-assembled on a NA surface. Addition of TNT to the sensor solution results in a concentration-dependent change in FRET. In this configuration, the sensor retains its analyte specificity yet can still have its dynamic sensing range usefully adjusted. The sensor can be washed free of analyte

10   and reforms for subsequent detection events. The demonstration that this sensor can be readily adapted to a completely different analyte highlights the utility of its modular construction and its general applicability to a variety of targets.

Explosive standards including TNT, TNB, hexa-hydro-1,3,5-trinitro-1,3,5-triazine (RDX), 2-amino-4,6-dinitrotoluene (2A-4,6-DNT), and 2,4-dinitrotoluene (2,4-DNT) were obtained from

15   Cerilliant Corp. (Austin, TX). Reactibind Neutravidin-coated plates were obtained from Pierce (Rockford, IL).

Mutagenesis and Protein Expression. The R-TNTscFv fragment, a derivative of TNB2 described in Goldman, et al, *Journal of Env. Monitor*; 2003, 5,380-3, was engineered to express a (His)$_6$GlyGlySerGlyGly(His)$_6$ carboxy terminus, where (His)$_6$ = 6-histidine residue sequence. Selected

20   cysteine mutations were introduced into the DNA coding sequence using the Quickchange Site-Directed Mutagenesis Kit (Stratagene, La Jolla, CA). For mutagenesis, polyacrylamide gel-purified oligonucleotides were obtained from Sigma Genosys (Woodlands, TX). Transformants were selected, and correct mutational residue changes were verified by DNA sequencing. α-TNTscFv-Cys mutants were expressed in the E. coli Tuner strain (Novagen, San Diego CA) and purified from the periplasm. α-

25   TNTscFv-Cys mutant samples were labeled with maleimide-activated AlexaFluor 532 dye (AFF 532: quantum yield 0.8, molar extinction coefficient 81 000 M^{-1} cm $^{-1}$; Molecular Probes, Eugene OR, with the modification of using 100× less of the dithiothreitol reducing agent. Dye-to-protein ratios of ~1 were obtained. Construction and purification of (His)$_6$-appended myoglobin, with a cysteine mutation at position 64, and its subsequent labeling with Cy3-maleimide (Amersham Bioscience, Piscataway, NJ).

30   ELISAs for determining TNB binding were performed on the α-TNTscFv-Cys mutants.

Dye-Labeled TNB DNA Arm: FIG. 3 depicts the dye-labeled TNB DNA arm. The precursor of the dye-labeled TNB DNA arm, purchased from Qiagen (Alameda, CA) was already modified with a teramethylrhodamine (TAMRA) dye-labeled internal T* base (quantum yield 0.7, molar extinction coefficient 91 000 M^{-1} cm $^{-1}$) and a 5'-amino modification on a C-6 linker. The DNA precursor

35   was subsequently reacted with a 1000-fold molar excess of 2,4,6-trinitrobenzene-sulfonic acid (5% solution, Sigma, St. Louis, MO), in 1 mL of 0.136 M sodium tetraborate buffer pH 8.5 supplemented with 20 μL of 2 M NaOH. The resulting solution was reacted overnight at room temperature under

continuous agitation, then loaded on a Supelclean LC-18 SPE column (Supelco, Bellefonte PA), washed
with 0.1× borate buffer, and eluted with an increasing concentration of methanol in borate buffer. The
mass of the final product (MW ~5878) was verified on an Applied Biosystems API QSTAR Pulsar mass
spectrometer by positive electrospray ioniza-tion.

5   Sensor Assembly: For each well of the Reactibind NA-coated plates (binding capacity ~60
pmol of biotin), 30 pmol of dye-labeled TNB DNA arm was added to 30 pmol of hybridizable flexible
DNA linker, heated to 90 °C for 5 min, and then cooled to room temperature slowly to preclude
secondary structure formation. The DNA melting temperature is ~62 °C. Concurrently, 30 pmol of
AlexaFluor 532-labeled α-TNTscFv was mixed with 30 pmol of biotin-X nitrilotriacetic acid

10   tripotassium salt precharged with nickel (Bio-X NTA, Biotium, Hayward CA, Bio-biotin, X-
aminomethoxy spacer, NTA-nitrilotriacetic acid chelator. After 2 hours, DNA and protein solutions were
mixed together (now equimolar), diluted with phosphate-buffered saline pH 7.4 (PBS) to a final volume
equivalent to 50 μL/well and incubated for 4h at room temperature. A 50-μL aliquot of sensor solution
was added to each well of the NA plates and incubated at 4 °C overnight. For regeneration, sensor-coated

15   plates were washed 10× with 200 μL of PBS and reconstituted in 50 μL of PBS for subsequent
retitration. For experiments utilizing modulator DNA, a 1:1 molar ratio of modulator DNA was added to
the primary DNA solution (DNA melting temperature is ~55 °C).

          Fluorometry and Titration. Fluorometric analysis was performed on a Safire dual
monochromator multifunction microtiter plate reader (Tecan, Boston, MA). Samples were excited at 510

20   nm, and emission was recorded at 600 nm. A 5-μL aliquot of 2× solution containing diluted explosive
was added to each well at room temperature for 5 minutes to give a final concentration in 100 μL. Each
point of a titration was performed in triplicate (three separate wells), and FRET efficiency at 600 nm was
monitored during experiments. Titrations are plotted against the change (loss) in fluorescence compared
to the 0 concentration point. In the figures, error bars appear where appropriate; if not, the error is within

25   the point value. Approximate binding constants K_{app} were estimated from the second derivative of
titration curves and rounded to whole integers.

          A homogeneously labeled α-TNTscFv protein and sensor was desirable. Site-specific
labeling of proteins is easily accomplished on unique cysteine residues. The current α-TNTscFv protein
already contains four cysteines, which are required to form intrachain disulfide bonds to stabilize the

30   variable heavy (VH) and variable light (VL) domains and help maintain the proteins' integrity and
recognition function. Since the introduction of additional cysteines could result in detrimental disulfide
bond formation during the expression and folding process and a nonfunctional "disulfide scrambled"
protein, an intuitive approach based on modeling and design was undertaken. A model was constructed
of the α-TNTscFv protein for the determination of optimum mutational sites. Selection criteria included

35   surface-exposed residues to facilitate labeling, proximity to peptide turns, location distal from the binding
site, location distal from the already present cysteines, and selection of residues, which, if changed,
would have minimal affect on overall structure. The four sites selected were Gln13, Leu145, Ala210, and

Ala241. Transformants were obtained for the first three mutational sites. The Ala241 site is proximal to

the $(His)_6GlyGlySerGlyGly(His)_6$, region and this may have interfered with mutagenic oligonucleotide

hybridization. After DNA sequence verification of the three mutants obtained, growth and induction

revealed that only the strains expressing the α-TNTscFv Ala210Cys and Leu145Cys mutants produced

5   any protein expression. TNB binding was assayed by ELISA, and results indicted that only the α-

TNTscFv-Leu145Cys mutant protein had any appreciable TNB binding capacity. This mutant was

subsequently dye-labeled with AFF 532 and still retained its TNB binding capacity when reassayed using

ELISA.

              Sensor Assembly, Titration versus TNT, and Regeneration. The sensor was assembled

10   using the AFF 532-labeled α-TNTscFv-Leu145Cys protein. Attempts at tethering the dye-labeled TNB

DNA arm and the labeled protein separately resulted in low amounts of functional sensor assembly; thus,

both elements were prebound prior to tethering to the NA surface. This is in contrast to the maltose

targeting prototype, which was assembled sequentially. By pre-binding prior to tethering, more active

sensor sites consisting of both elements in functional orientations were attached to the surface and

15   available for regeneration after washing. Following sensor self-assembly, TNT in solution was titrated.

The resulting loss of FRET-based fluorescence at 600 nm was plotted against the concentration. TNT

concentrations higher than 50 mg/L were not used, as TNT solubility in aqueous solutions saturates at

concentrations approaching 100 mg/L. A lower limit of detection of 1 mg/L TNT (1 part per

million/ppm) was noted for this sensing assembly. The binding curve appears to be a relatively linear

20   function over this series of concentrations tested. The sensor assembly was washed using 10 volumes of

200 μL PBS and then regenerated in 50 μL of PBS for 24h at 4 °C. A second TNT titration was

performed, the sensor washed and then regenerated for 1hour at room temperature, and then a third

titration was performed.. Similar control experiments performed using sensor assemblies incorporating a

dye-labeled DNA arm lacking the TNB moiety or substituting Cy3-labeled myoglobin for the α-

25   TNTscFv resulted in no change in fluorescence upon TNT addition. Additionally, the 600-nm TAMRA

emission for these control assemblies was substantially lower, also indicative of inefficient FRET. These

results confirm that the same sensor binding of the terminal DNA arm recognition analogue and sensor

regeneration performance seen in the maltose sensing prototype is present in the current TNT sensing

assembly.

30   Sensor Specificity and Modulation. To determine specificity and cross-reactivity, sensor

assemblies were tested against a variety of TNT structural analogues. Not surprisingly, TNB elicited the

highest sensor response in terms of absolute fluorescence change, followed closely by TNT. This result

can be attributed to the fact that the antibody fragment was originally selected against TNB and the

analogue attached to the DNA arm is also TNB. Thus, TNB will be the most effective competitor for

35   binding sites. RDX and 2-A-4,6-DNT caused significantly less response, with 2,4-DNT eliciting the least

response. Since 2-A-4,6-DNT elicits all of its response between 5 and 20 mg/L, the result is almost a

complete "classical" binding curve in comparison to the results elicited from the other explosive

compounds. It should be noted that, in this format, TNT cannot be distinguished from the structurally   -
related competitors until higher concentrations. As mentioned, issues of solubility limit the concentration
range that can be tested for these compounds, limiting them to the "linear" portion of the curve.
Nevertheless, these results very closely parallel the competition ELISA format used to test the precursor

5   anti-TNB scFv selected. This demonstrates that the original α-TNTscFv specificity is retained even after
multiple modifications including the following: (1) appending a (His)$_6$-spacer-(His)$_6$, (2) point mutation
to a cysteine, (3) dye labeling of the cysteine, (4) surface tethering, and (5) interacting with the dye-
labeled TNB DNA arm as part of sensing. This also parallels the specificity retained by the maltose
sensing prototype after similar modifications.

10   The dynamic sensing range of the maltose sensing prototype could be modulated by
"stiffening" of the tether arm through the addition of a DNA complementary to the DNA linker.
Although the binding constant essentially remained the same, the binding curve of the modulated
prototype became broader, significantly increasing the useful sensing range. Similar experiments were
performed with the current TNT sensing assembly. During self-assembly, modulator DNA was added to

15   the hybridizable flexible DNA linker, significantly increasing the amount of double-stranded DNA from
16 of 44 bases (~35%) in the unmodulated sensor to 36/44 (~80%) when modulated. The lower limit of
TNT detection of the modulated sensor dropped ~10-fold from 1 to 0.1 mg/mL (1 ppm to 100 parts per
billion/ppb). In parallel to the prototype, these results show that the modulation mechanism can be
exploited to adjust useful sensor properties. The choice of C6 chain, 5'-amino-C6 and 15-carbon spacer in

20   the DNA arm was driven by availability for incorporation during automated DNA synthesis. It should be
noted that adjusting the length of the single-stranded DNA arm (as opposed to rigidity) in the maltose
sensing prototype did not effect binding properties. Thus, adjusting these alkane moieties in terms of
length were not considered critical in the current sensor as well. "Switching in" of a more sensitive scFv
antibody fragment would be another mechanism of adjusting sensor properties.

25   The TNT sensing assembly demonstrated retains almost all of the desirable properties of
the MBP-based prototype while targeting a different analyte. Among the useful features of this sensor are
the use of robust avidin-biotin technology for surface tethering and the ease of self-assembly in a
microtiter plate format, which also facilitates analysis by readily accessible fluorescent plate readers. The
prototype and current sensor use dye-based FRET; however, signal transduction may be expanded to

30   other proximity-sensitive methods such as electrochemical detection. The choices of FRET dyes and their
locations on either module are also interchangeable, which can allow optimization to address any
potential distance requirements. Furthermore, the sensor can be regenerated for subsequent reuse. In
these experiments, an upper limit of 6-8 regenerations was obtained. Regeneration in less than 1 hour is
feasible. Sensor response in the current microtiter well format is limited by technician handling time,

35   which suggests that real-time sensing in a flow cell is feasible.

                The modularity of the sensor design disclosed is demonstrated by readily adapting it to
target another analyte. As such, the sensitivity of the biorecognition element was not a major criterion.

However, this does not preclude the current sensor from actual use as a solution-phase TNT sensor. More sensitive (His)$_6$-appended TNT recognition elements are available that demonstrate nanomolar sensitivity. The current α-TNTscFv fragment could undergo another round of evolution to select for higher affinity mutants. Although the modulated behavior of the sensor was modest, ~10-fold decrease

5   in limit of detection, the conservation of this feature seen is important. The addition of DNA to stiffen the arm creates sensors that are more sensitive to perturbation, thus increasing sensitivity and yielding a lower limit of detection. Due to the issues of TNT solubility, the same broadening of the dynamic sensing range with DNA stiffening could not be fully tested. However, this result suggests that modulation through careful control of arm stiffness/kinetics can be further exploited to yield sensing assemblies with

10   variable control over the desired affinities. The combination of "switching in" of mutant proteins with different affinities and sensor arm modulation may also potentiate the sensitivity attainable.

The modular nature and adaptability of this sensor design can easily be adapted to target another analyte and yet remain functionally robust. Choices of biorecognition elements that can fit directly into the current format include (His)$_6$-appended proteins such as bPBPs, scFv fragments, or even

15   soluble fragments of cloned cellular receptors. The (His)$_6$ motif is commonly engineered into many cloned proteins for facile purification over Ni-NTA media. Additionally, an analogue of the primary analyte of interest must be attached to the distal end of the DNA arm and many covalent and noncovalent chemical linking strategies are known in the art to address this. A variety of choices are available for both the biorecognition module and the modular arm. Adaptation of this sensor for testing in a drug discovery

20   assay where a variety of compounds with differing affinities for the biorecognition module can be screened in parallel is possible. Multianalyte or "multiplex" sensing is another possibility. Other applications may include providing a variety of sensors in a microtiter well format for screening or quantitation of many different analytes such as in a clinical setting. Sensor assemblies can be dried, stored, and reconstituted for later use. This suggested that sensors could be assembled on microtiter

25   plates and dried/stored for later use in other locations. Although demonstrated in a microtiter well plate format, assembly of these sensors in flow cells and on other surfaces, including nanoparticle surfaces, is possible.

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the

30   invention may be practiced otherwise than as specifically described.

CLAIMS

What is claimed is:

1. A modular biosensor comprising:

   a biorecognition element, comprising a biorecognition module, said biorecognition module being labeled with a first signaling module;

   a modular arm element modular arm element, comprising of a flexible arm and a recognition module, wherein said modular arm element is labeled with a second signaling module, wherein said modular arm element is specifically oriented in reference to the biorecognition element, wherein said biorecognition element is linked to said modular arm element, wherein said biorecognition module and said recognition module of said modular arm element bind, wherein said first and second signaling modules are in close proximity to each other to establish a baseline fluorescence resonance energy transfer (FRET); and

   a detector for detecting a change in FRET.

2. The modular biosensor of Claim 1, wherein said biorecognition element is linked to said modular arm element either covalently or non-covalently.

3. The biosensor of Claim 1, wherein said signaling module is a dye, a quencher, an electrochemically active group, a quantum dot or an enzyme.

4. The biosensor of Claim 1, wherein said biorecognition module is a protein, an enzyme, a receptor, a bacterial periplasmic binding protein, an antibody fragment, a peptide, an aptamer, a carbohydrate, DNA, PNA, RNA, or other macromolecule.

5. The biosensor of Claim 1, wherein said biorecognition module is at least one protein, an enzyme, a receptor, a bacterial periplasmic binding protein, an antibody fragment, a peptide, an aptamer, a carbohydrate, DNA, PNA, RNA, or other macromolecule.

6. The biosensor of claim 1, wherein the flexible arm is comprised of a SS-DNA, a DS-DNA, a combination of a SS-DNA and aDS-DNA, a thiolated DNA, a RNA, a thiolated RNA, a linear homopolymer, a linear copolymer, a block copolymer, a PNA, an α peptides, a β peptides, a protein, a polymer, or an oligosaccharide.

7. The biosensor of claim 1, wherein the recognition module is comprised of at least one antigen, epitope, analyte, substrate, protein, peptide, toxin, sugar, biological agent, or

analogs of said antigen, epitope, analyte, substrate, protein, peptide, toxin, sugar, or biological agent.

8. The modular biosensor of Claim 1, wherein said biorecognition element is attached to a surface by a surface attachment module by surface attachment.

9. The biosensor of Claim 8, wherein said surface attachment module is comprised of biotin, avidin, antibody, reactive thiol, reactive amine, non-reversible enzyme substrate, protein A, protein G, protein L, DS-DNA, or PNA.

10. The biosensor of Claim 8, wherein said surface attachment is biotin-avidin chemistry, metal-affinity coordination, thiol bonding, hydrophobic interactions, or DNA-directed immobilization.

11. The biosensor of claim 8, wherein said surface is comprised of a polystyrene micro-titer plate well, a solid planar macromaterial, a spherical or other shaped material, a microscopic planar, spherical or other shaped micro- or nanomaterial, a nanocrystalline, a modified nanocrystalline material; a molecular or biomolecular assembly composed of protein, DNA, RNA, PNA, morpholino DNA, or other biomolecule and their derivatives, a molecularly templated material, a polymer, or a mineral.

12. The biosensor of claim 1, wherein said biorecognition element and said modular arm element have a specific binding affinity.

13. The biosensor of claim 12, wherein said specific binding affinity is modulated by altering said biorecognition module.

14. The biosensor of Claim 12, wherein said specific binding affinity is modulated by temperature.

15. The biosensor of Claim 12, wherein said specific binding affinity is modulated by altering the properties of the flexible arm of the modular arm element.

16. A modular biosensor comprising:

a biorecognition element, comprising a biorecognition module, said biorecognition module being labeled with a first signaling module, said biorecognition element being attached to a surface;

a modular arm element modular arm element, comprising of a flexible arm and a recognition module, said modular arm element being attached to a surface, wherein said modular arm element is labeled with a second signaling module, wherein said modular arm element is specifically oriented in reference to the biorecognition element, wherein said biorecognition module and said recognition module of said modular arm element bind, wherein said first and second signaling modules are in close proximity to each other to establish a baseline fluorescence resonance energy transfer (FRET); and

a detector for detecting a change in FRET.

17. The biosensor of Claim 16, wherein said signaling module is a dye, a quencher, an electrochemically active group, a quantum dot or an enzyme.

18. The biosensor of Claim 16, wherein said biorecognition module is a protein, an enzyme, a receptor, a bacterial periplasmic binding protein, an antibody fragment, a peptide, an aptamer, a carbohydrate, DNA, PNA, RNA, or other macromolecule.

19. The biosensor of claim 16, wherein the flexible arm is comprised of a SS-DNA, a DS-DNA, a combination of a SS-DNA and aDS-DNA, a thiolated DNA, a RNA, a thiolated RNA, a linear homopolymer, a linear copolymer, a block copolymer, a PNA, an α peptides, a β peptides, a protein, a polymer, or an oligosaccharide.

20. The biosensor of claim 16, wherein the recognition module is comprised of at least one antigen, epitope, analyte, substrate, protein, peptide, toxin, sugar, biological agent, or analogs of said antigen, epitope, analyte, substrate, protein, peptide, toxin, sugar, or biological agent.

21. The modular biosensor of Claim 16, wherein said biorecognition element is attached to a surface by a surface attachment module by surface attachment.

22. The biosensor of Claim 21, wherein said surface attachment module is comprised of biotin, avidin, antibody, reactive thiol, reactive amine, non-reversible enzyme substrate, protein A, protein G, protein L, DS-DNA, or PNA.

23. The biosensor of Claim 21, wherein said surface attachment is biotin-avidin chemistry, metal-affinity coordination, thiol bonding, hydrophobic interactions, or DNA-directed immobilization.

24. The biosensor of claim 21, wherein said surface is comprised of a polystyrene micro-titer plate well, a solid planar macromaterial, a spherical or other shaped material, a microscopic planar, spherical or other shaped micro- or nanomaterial, a nanocrystalline, a modified nanocrystalline material, a molecular or biomolecular assembly composed of protein, DNA, RNA, PNA, morpholino DNA, or other biomolecule and their derivatives, a molecularly templated material, a polymer, or a mineral.

25. The biosensor of claim 16, wherein said biorecognition element and said modular arm element have a specific binding affinity.

26. The biosensor of claim 25, wherein said specific binding affinity is modulated by altering the biorecognition module of said biorecognition element.

27. The biosensor of Claim 25, wherein said specific binding affinity is modulated by providing a plurality of biorecognition modules on said biorecognition element.

28. The biosensor of Claim 25, wherein said specific binding affinity is modulated by controlling the temperature.

29. The biosensor of Claim 25, wherein said specific binding affinity is modulated by altering the properties of the flexible arm of the modular arm element.

30. A biosensor for detecting the presence of an analyte, comprising:

a biorecognition element, comprising a biorecognition module, said biorecognition module being labeled with a first signaling module, said biorecognition element being attached to a surface by a surface attachment module;

a modular arm element comprising of a flexible arm and a recognition module, said modular arm element being attached to a surface by a surface attachment module, wherein said modular arm element is labeled with a second signaling module, wherein said modular arm element is specifically oriented in reference to the biorecognition element, wherein said biorecognition module and said recognition module of said modular arm element bind, wherein said first and second

signaling modules are in close proximity to each other to establish a baseline

fluorescence resonance energy transfer (FRET), wherein said baseline FRET changes

measurably in the presence of the analyte; and

        a detector for detecting a change in FRET in the presence of the analyte.

31. A method of making a modular biosensor, comprising the steps of:

synthesizing a biorecognition module;

labeling the biorecognition module with a signaling module;

synthesizing a modular arm element;

labeling the modular arm element with a signaling module;

linking the biorecognition module to the modular arm element; and

binding the biorecognition module and the modular arm element by self assembly to

establish a baseline FRET.

32. A method of making a modular biosensor, comprising the steps of:

synthesizing a biorecognition module;

labeling the biorecognition module;

synthesizing a modular arm element;

labeling the modular arm element;

attaching the biorecognition module and the modular arm element to a surface; and

binding the biorecognition module and the modular arm element by self assembly to

establish a baseline FRET.

33. A method of making a modular biosensor, comprising the steps of:

synthesizing a biorecognition module;

labeling the biorecognition module;

synthesizing a modular arm element;

labeling the modular arm element;

binding the biorecognition module and the modular arm element by self assembly to

establish a baseline FRET; and

attaching the biorecognition module and the modular arm element to a surface.

34. A biosensor array comprising a plurality of biosensors, wherein at least one of the

plurality of sensors is a sensor according to claim 1.

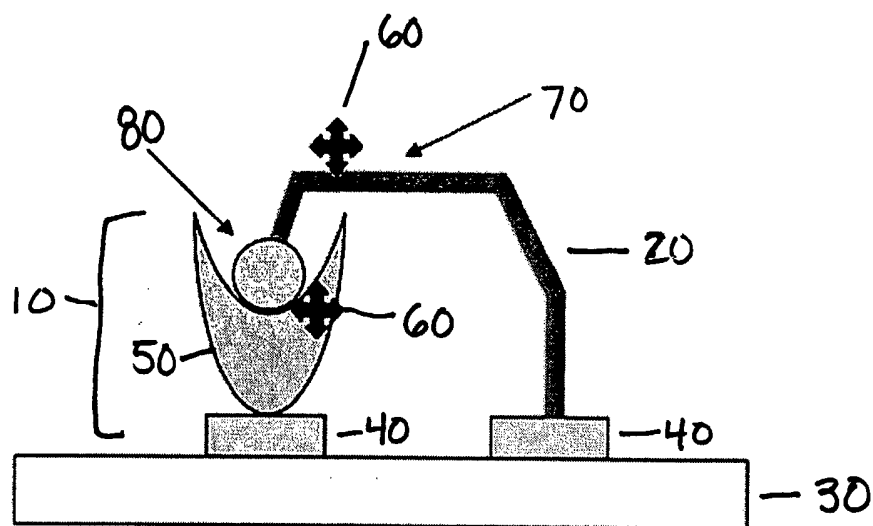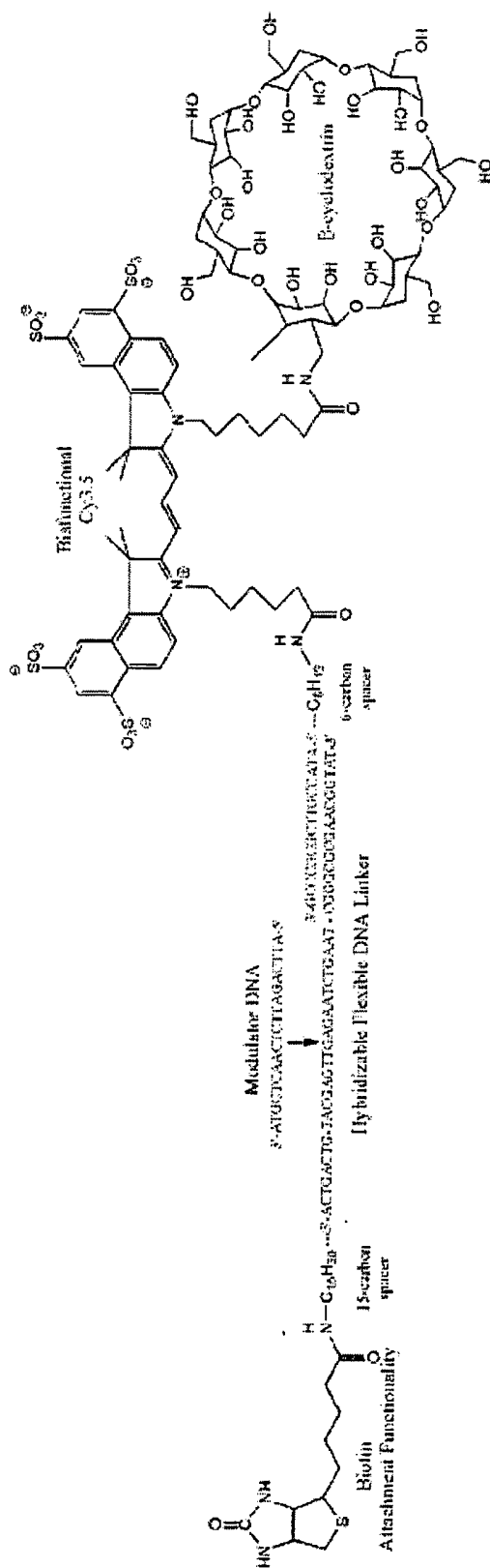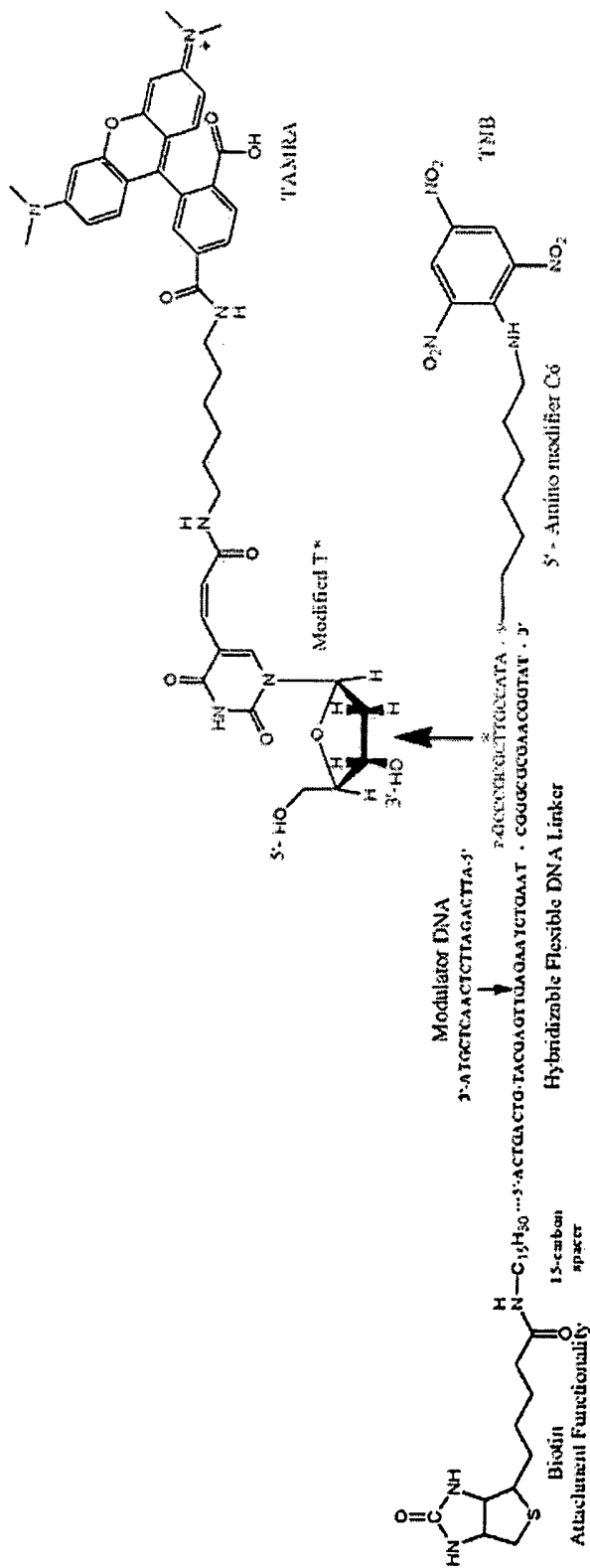35. A sensor array according to claim 34, wherein each of the sensors is a sensor
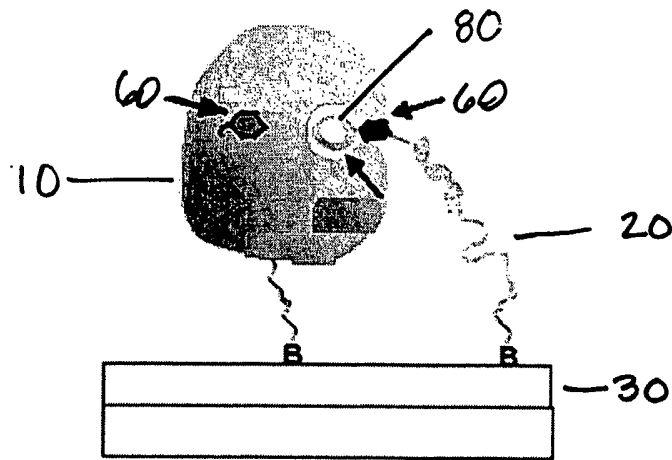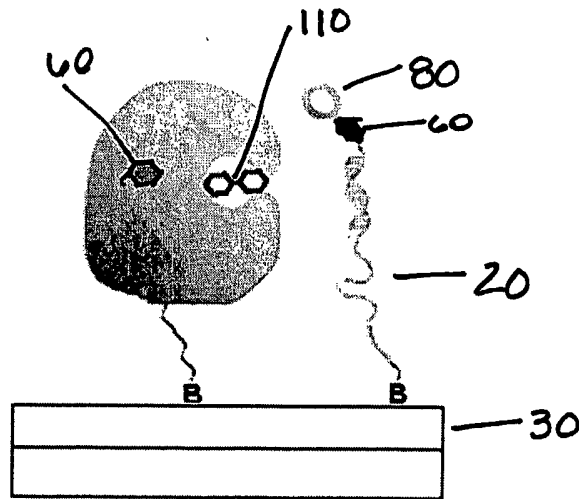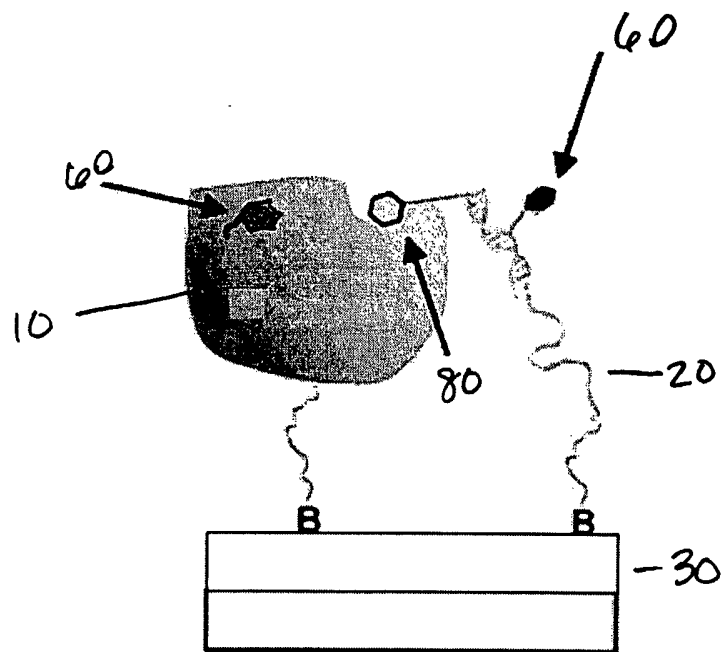
according to claim 1.

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

FIG 5a

FIG 5b

FIG 6

FIG 7

FIG 8