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DNA biochip and methods of use

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Kumar et al.

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(54) **DNA BIOCHIP AND METHODS OF USE**

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USPC ... **435/6.1**; 435/283.1; 435/287.2; 422/82.01; 536/23.1

(58) **Field of Classification Search**
None
See application file for complete search history.

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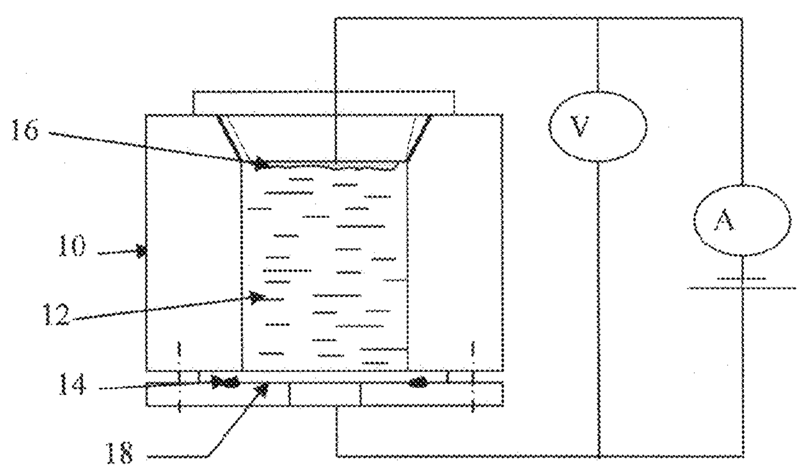
(57) **ABSTRACT**

The subject invention concerns materials and methods for detecting nucleic acid sequences. One aspect of the invention concerns a silicon-based "biochip" comprising nucleic acid immobilized thereon. In one embodiment, the silicon comprises microcavities. The nucleic acid to be assayed for the presence of one or more target nucleic acid sequences is immobilized on the silicon. A nucleic acid, such as an oligonucleotide probe, having a sequence substantially complementary to the target nucleic acid sequence can be used to detect the immobilized nucleic acid on the silicon. If the nucleic acid used for detection hybridizes with a target nucleic acid sequence, the hybridized sequences can be detected directly or indirectly. In an exemplified embodiment, the oligonucleotide probe can be labeled with a detectable label, for example, a fluorescent molecule. The subject invention also concerns methods for detecting a target nucleic acid using a silicon-based biochip of the invention.

10 Claims, 9 Drawing Sheets
(6 of 9 Drawing Sheet(s) Filed in Color)



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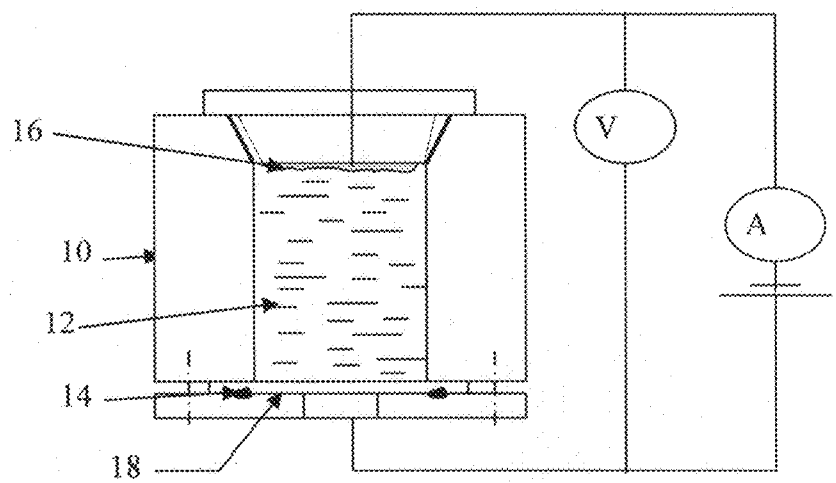


FIG. 1

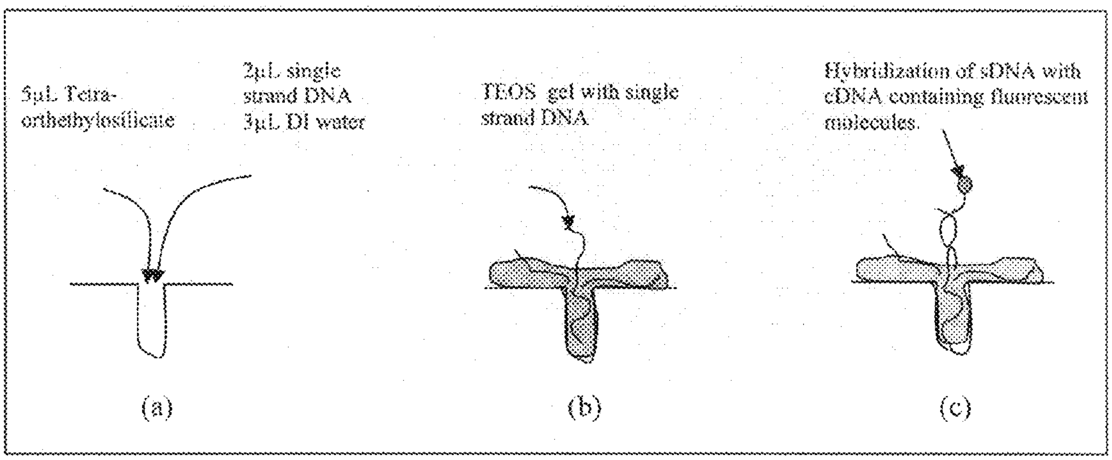

5μL Tetra-orthethylosilicate
2μL single strand DNA
3μL DI water
TEOS gel with single strand DNA
Hybridization of sDNA with cDNA containing fluorescent molecules.
(a)
(b)
(c)

FIG. 2

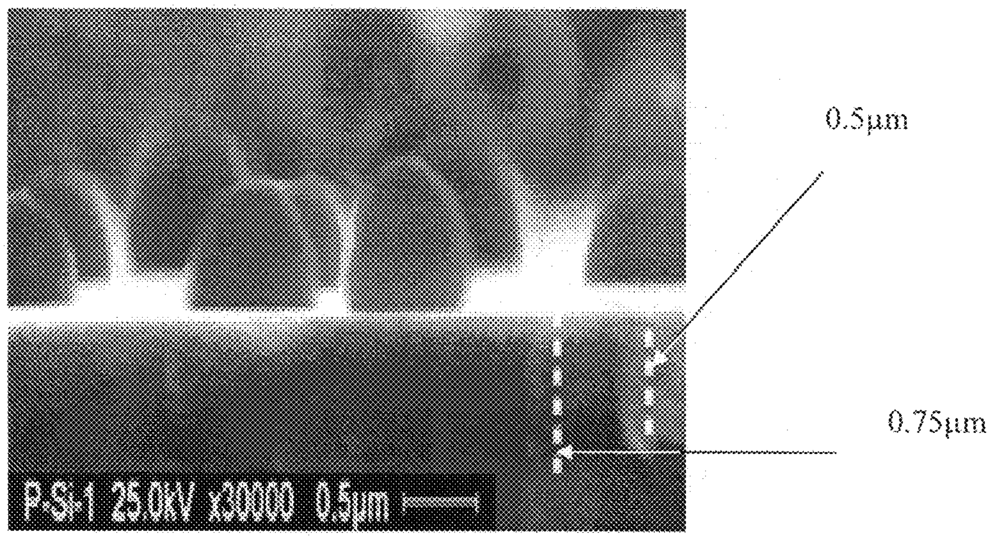


FIG. 3

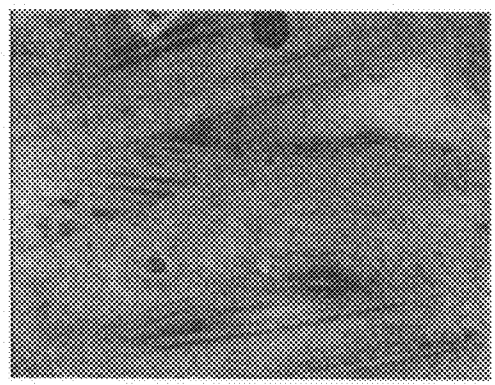


FIG. 4A

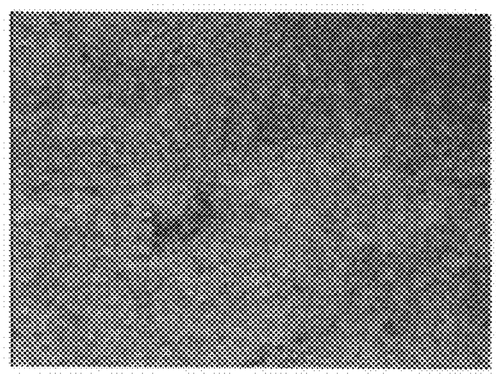


FIG. 4B

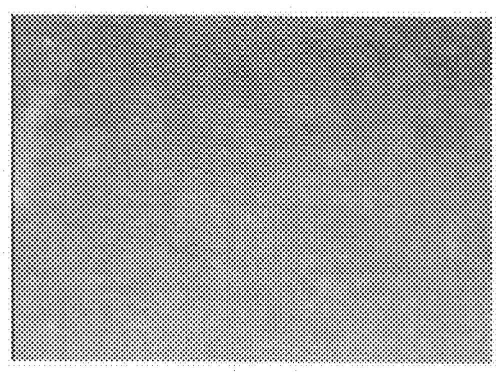


FIG. 4C

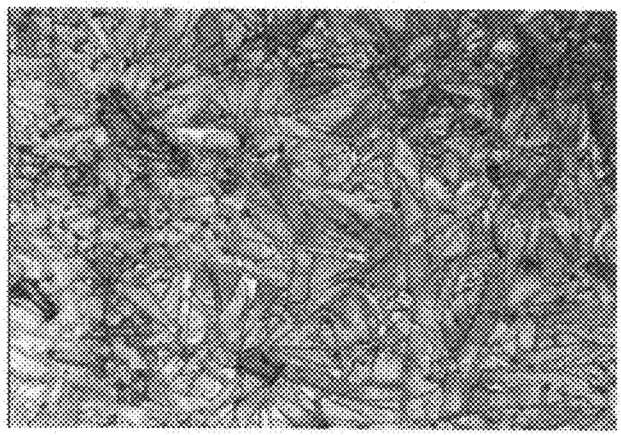


FIG. 5A

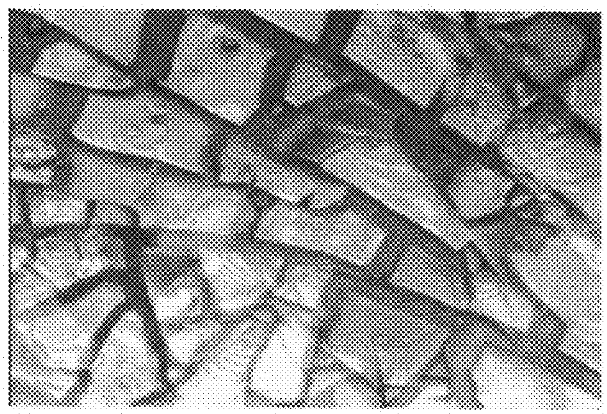


FIG. 5B

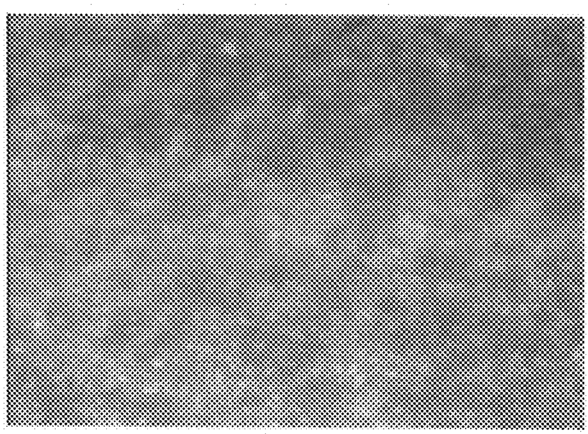


FIG. 5C

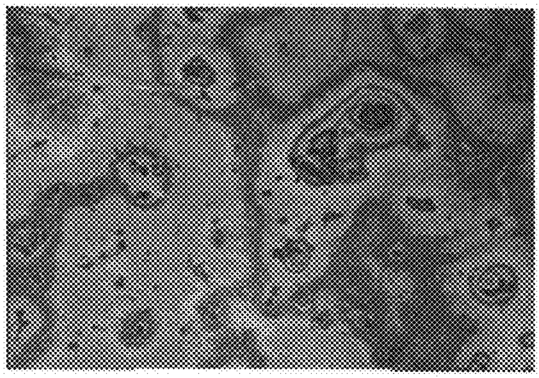


FIG. 6A

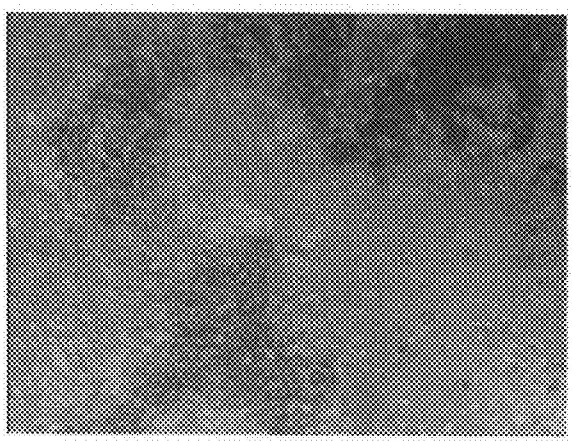


FIG. 6B

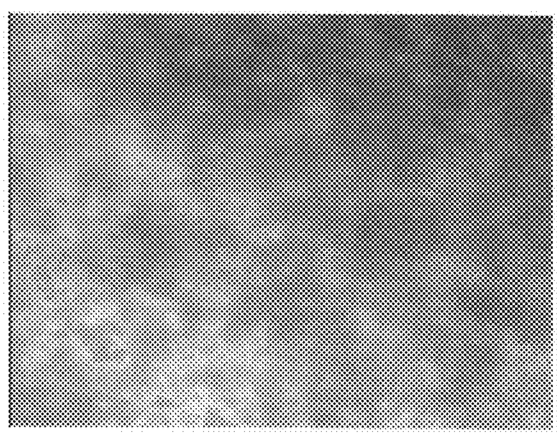


FIG. 6C

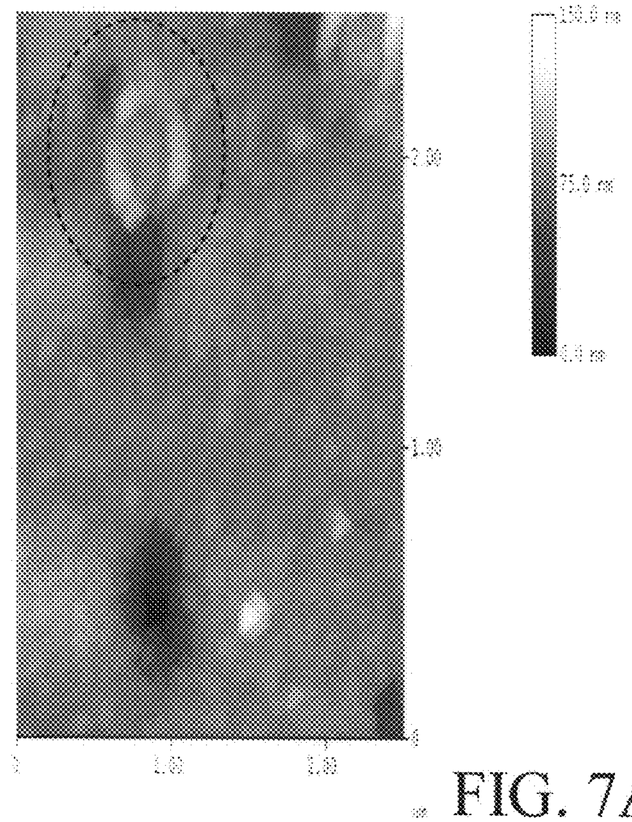


FIG. 7A

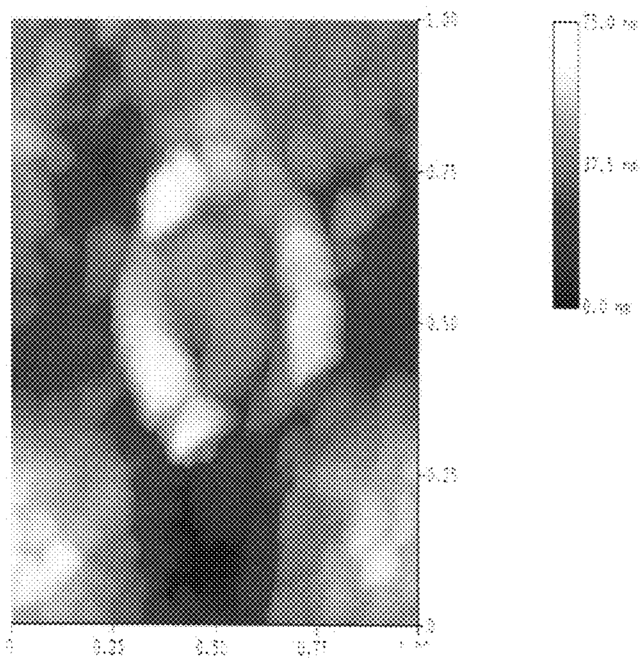


FIG. 7B

psi

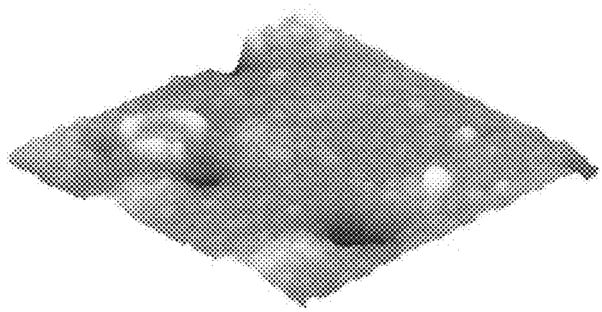


FIG. 8A

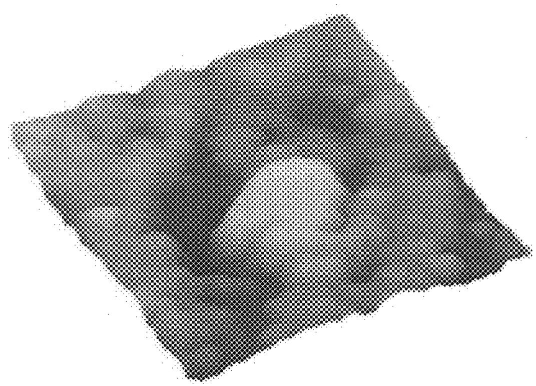
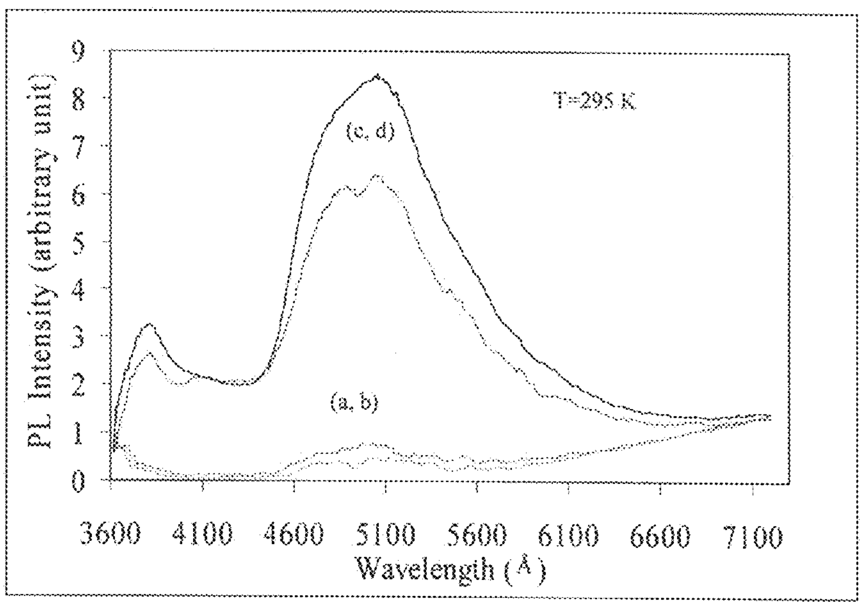


FIG. 8B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(c, d)
(a, b)
Wavelength (Å)
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2
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7
8
9
3600
4100
4600
5100
5600
6100
6600
7100

FIG. 9

DNA BIOCHIP AND METHODS OF USE

CROSS-REFERENCE TO A RELATED APPLICATIONS

This application is a divisional of U.S. application Ser. No. 11/347,438, filed Feb. 3, 2006, now U.S. Pat. No. 7,875,426, which claims the benefit of U.S. Provisional Application Ser. No. 60/649,961, filed Feb. 4, 2005, each of which is hereby incorporated by reference herein in its entirety, including any figures, tables, and drawings.

BACKGROUND OF THE INVENTION

DNA plays an important role in many cellular processes like replication, homologous recombination and transcription. Besides its genomic information, DNA exhibits very interesting biophysical and physicochemical properties which are essential for proper functioning of the biomolecular processes involved. Biochips, particularly those based on DNA are powerful devices that integrate the specificity and selectivity of biological molecules with electronic control and parallel processing of information. This combination will potentially increase the speed and reliability of biological analysis. Microelectronic technology is especially suited for this purpose since it enables low-temperature processing and thus allows fabrication of electronics devices on a wide variety of substances like glass, plastic, stainless steel and silica wafer. Fundamental phenomena like molecular elasticity, binding to protein, supercoilling and electronic conductivity also depends on the numerous possible DNA confirmations and can be investigated nowadays on a single molecule level. Experiments with single DNA have been reported with scanning tunneling microscopy (Guckenberger et al., 1994), fluorescence microscopy (Yanagida et al., 1983), fluorescence correlation spectroscopy (Wannmalm et al., 1997), optical tweezers (Smith et al., 1996), bead techniques in magnetic fields (Wang et al., 1997), optical microfibers (Strick et al., 1996), electron holography (Smith et al., 1992a) and atomic force microscopy (Cluzel et al., 1996; Fink et al., 1999; Hansma et al., 1991). All these methods provide, directly or indirectly, information on molecular structure and function. They differ, however, in the molecular properties they probe, their spatial and temporal resolution, their molecular sensitivity and working environment.

Fluorescently labeled oligonucleotide probes are in regular use for nucleic acid sequencing (Mirzabekov, 1994), sequencing by hybridization (SBH) (Speel et al., 1999), fluorescence in situ hybridization (FISH) (Lakowicz et al., 1999), fluorescence resonance energy transfer (FRET) (Selvein, 2000), molecular beacons (Singh et al., 2000), taqman probes (Broude, 2002), and chip-based DNA arrays (Wittwer et al., 1997). This has made fluorescent probes an important tool for clinical diagnostics and made possible real-time monitoring of oligonucleotide hybridization. Furthermore, fluorescent-based diagnostics avoid the problem of storage, stability, and disposal of radioactive labels (Schena, 2000; Drobyshov et al., 1997).

Knowledge of structural and physical properties in microbial cells and microbial cell components is required to obtain a comprehensive understanding of cellular process and their dynamics. The need for a nondestructive method was satisfied with the development of the Atomic Force Microscope (AFM). The last 15 years have witnessed the extraordinary growth of structural studies in biology, and the impact is being felt in almost all areas of biological research. Several groups have used microscopy for the analysis of DNA, protein, and

DNA-protein interactions. Until recently, electron microscopy was used as the main tool for imaging DNA; however this technique can be harsh on biological samples, making successful analysis extremely difficult. Approximately a decade ago, scientists began to use AFM for the analysis of biological samples. AFM allowed the analysis of biological molecules to be performed faster, easier and more accurately yielding successful characterization of biological specimens. The development of the AFM and its introduction for imaging biological samples has provided scientists with a very powerful tool to explore many aspects of protein-protein, protein-DNA and many other interactions (Fritz et al., 2000).

Various methods can be employed to bind DNA to different hosts. An array of substances, including catalytic antibodies, DNA, RNA, antigens, live bacterial, fungal, plant and animal cells, and whole protozoa, have been encapsulated in silica, organosiloxane and hybrid sol-gel materials. Sol-gel immobilization leads to the formation of advanced materials that retain highly specific and efficient functionality of the guest biomolecules within the stable host sol-gel matrix (Hench et al., 1990). The protective action of the sol-gel cage prevents leaching and significantly enhances stability of biomolecules within the sol-gel. The advantages of these 'living ceramics' might give them applications as optical and electrochemical sensors, diagnostic devices, catalysts, and even bio-artificial organs. With rapid advances in sol-gel precursors, nanoengineered polymers, encapsulation protocols and fabrication methods, this technology promises to revolutionize bioimmobilization. Biosensors using immobilized receptors are finding ever-increasing application in a wide variety of fields such as clinical diagnostics, environmental monitoring, food and drinking water safety, and monitoring of illicit drugs (Brinker et al., 1985). One of the most challenging aspects in development of these sensors is immobilization and integration of biological molecules in the sensor platform. Numerous techniques, including physical covalent attachment, and entrapment in polymer and inorganic matrices, have been explored over the past decade. Sol-gel processes are promising host matrices for encapsulation of biomolecules such as enzymes, antibodies, and cells (Kumar et al., 2000).

Porous silicon (PS) was discovered in 1956 by Uhlir (Uhlir, 1956) while performing electropolishing experiments on Silicon wafers using a hydrofluoric acid (HF)-containing electrolyte. Uhlir found that by increasing the current over a certain threshold, a partial dissolution of the silicon wafer started to occur. Porous Silicon formation can be obtained by electrochemical dissolution of Silicon wafers in aqueous or ethanoic HF solutions.

Microcavities are of interest for a wide range of fundamental and applied studies, including investigations of cavity quantum electrodynamics (Smith et al., 1992b), optical elements for telecommunications (Goryachev et al., 2003), single-photon sources (Chan et al., 2000), and chemical or biological sensors (Isola et al., 1998). Microfabrication techniques allow reproducible fabrication of resonators with lithographically controlled dimensions. Using a combination of lithography and etching, semiconductor microcavities have been obtained.

Almost all children under two years of age are infected by RSV. Children with weaker immune systems are at greater risk. For better health of all infants, infants with symptoms of common cold, wheezing, pneumonia and bronchiolitis need to be diagnosed for the RSV infection. All hospitals and physicians providing pediatric health care need RSV diagnosis kits. Current methods of detection are based on one single technology, i.e., immunological assays and they are very expensive and have low sensitivity and specificity. A new

more robust technology is needed to diagnose children infected with RSV with higher sensitivity and specificity and at a very lower cost.

BRIEF SUMMARY OF THE INVENTION

The subject invention concerns materials and methods for detecting a target nucleic acid comprising a nucleotide sequence of interest. One aspect of the invention concerns a silicon-based "biochip" comprising nucleic acid immobilized thereon. In one embodiment, the silicon-based biochip comprises microcavities. The nucleic acid to be assayed for the presence of one or more target nucleic acid sequences is immobilized on the silicon. In one embodiment, the nucleic acid is provided in a sol-gel composition. The nucleic acid can be immobilized in single stranded form. A detector nucleic acid, such as an oligonucleotide probe, having a sequence substantially complementary to the target nucleic acid sequence can be used to detect the immobilized nucleic acid on the silicon. If the nucleic acid used for detection hybridizes with a nucleotide sequence of a nucleic acid immobilized on the silicon, the hybridized sequences can be detected by direct or indirect means and thus the target nucleic acid is thereby detected. In an exemplified embodiment, the oligonucleotide probe can be labeled with a detectable label, for example, a fluorescent molecule.

The subject invention also concerns methods for detecting a target nucleic acid using a silicon-based biochip of the invention. In one embodiment, a sample to be tested for the presence of a target nucleic acid is contacted with a silicon biochip of the invention such that nucleic acid in the sample is immobilized on the silicon biochip. Preferably, the silicon is prepared so as to have microcavities. The nucleic acid to be assayed for the presence of one or more target nucleic acid sequences can be provided on the silicon surface in a sol-gel. The silicon biochip is then contacted with a detector nucleic acid that comprises a nucleotide sequence that is substantially complementary with the sequence of the target nucleic acid of interest under conditions that permit hybridization of the detector nucleic acid to the target nucleic acid. In one embodiment, the detector nucleic acid is labeled with a detectable moiety, such as a fluorescent molecule. Hybridization of the detector nucleic acid is indicative of the presence of the target nucleic acid. The present methods can be used to detect nucleic acid sequences associated with bacteria, viruses, fungi, protozoans, and the like. In an exemplified embodiment, the target nucleic acid sequence is from Respiratory Syncytial Virus (RSV).

BRIEF DESCRIPTION OF THE FIGURES

The file of this patent contains at least one drawing executed in color. Copies of this patent with the color drawings will be provided by the Patent and Trademark Office upon request and payment of the necessary fee.

FIG. **1** shows the schematics of electrochemical etching of a silicon wafer.

FIGS. **2**A-**2**C show the preparation of DNA fixation and hybridization with fluorescent molecules on porous silicon (PS) using TEOS.

FIG. **3** shows an SEM picture of porous silicon.

FIGS. **4**A-**4**C show images of porous silicon with microcavities through Optical Microscopic investigation of DNA biochip; FIG. **4**A (10×), FIG. **4**B (40×) and FIG. **4**C (100×).

FIGS. **5**A-**5**C show porous silicon microcavities attached with sDNA through Optical Microscopic investigation of DNA biochip; FIG. **5**A (10×), FIG. **5**B (40×) and FIG. **5**C (100×).

FIGS. **6**A-**6**C show DNA hybridization with fluorescence attached cDNA molecule with sDNA through Optical Microscopic investigation of DNA biochip; FIG. **6**A (10×), FIG. **6**B (40×) and FIG. **6**C (100×).

FIG. **7**A shows single stranded DNA attached to microcavity and FIG. **7**B shows a magnified view of single stranded DNA attached to microcavity.

FIG. **8**A shows a 3D AFM picture of an sDNA bundle attached to microcavity on silicon wafer and FIG. **8**B shows an AFM Images analysis of DNA hybridization (interaction of sDNA with cDNA.

FIG. **9** shows PL spectra of: sample "a" and "b" (sDNA on porous silicon), and PL spectra of sample "c" and "d" (cDNA hybridized to sDNA on porous silicon).

BRIEF DESCRIPTION OF THE SEQUENCES

SEQ ID NO: 1 is an oligonucleotide sequence corresponding to a sequence in the genome of Respiratory Syncytial Virus (RSV) F that is used in an exemplified embodiment of the present invention.

SEQ ID NO: 2 is an oligonucleotide sequence that is complementary to the sequence of SEQ ID NO: 1 and that is used in an exemplified embodiment of the present invention.

SEQ ID NO: 3 is the genomic nucleotide sequence for a Respiratory Syncytial Virus.

DETAILED DESCRIPTION OF THE INVENTION

The subject invention concerns materials and methods for detecting a target nucleic acid. One aspect of the invention concerns a silicon-based "biochip" comprising nucleic acid immobilized thereon. In one embodiment, the silicon comprises microcavities. Nucleic acid that is to be assayed for the presence of one or more target nucleic acid sequences is immobilized on the silicon. In one embodiment, the nucleic acid is immobilized in single stranded form. In a further embodiment, the nucleic acid is immobilized on the silicon using a sol-gel composition.

Sol-gel compositions and methods for incorporating a biomolecule, such as a nucleic acid, in sol-gel compositions are known in the art and have been described in U.S. Pat. Nos. 6,495,352 and 6,303,290, and in Kumar et al. (2000). A nucleic acid, such as an oligonucleotide probe, having a nucleotide sequence substantially complementary to a target nucleic acid sequence can be used to detect the immobilized nucleic acid on the silicon. If the nucleic acid used for detection hybridizes with a target nucleic acid sequence, the hybridized sequences can be detected either by direct or indirect means. In an exemplified embodiment, a nucleic acid (e.g., an oligonucleotide probe) can be labeled with a detectable label, for example, a fluorescent molecule.

The subject invention also concerns methods for detecting a target nucleic acid using a silicon-based biochip of the invention. In one embodiment, a sample to be tested for the presence of a target nucleic acid is contacted with the surface of a silicon biochip of the present invention such that nucleic acid present in the sample binds to and becomes immobilized on the silicon. Preferably, the silicon is prepared so as to have microcavities. The nucleic acid containing sample to be assayed for the presence of one or more target nucleic acid sequences can be provided on the silicon surface in a sol-gel composition. Optionally, the biochip can be washed to remove unbound nucleic acid. The silicon biochip is then contacted with a detector nucleic acid that comprises a nucleotide sequence that is substantially complementary with the sequence of the target nucleic acid of interest under condi-

tions that permit hybridization of the detector nucleic acid to the target nucleic acid but that exclude non-specific binding of nucleic acid (i.e., conditions are such that nucleic acid that does not have a nucleotide sequence substantially complementary with the sequence of a target nucleic acid does not bind to the target nucleic acid or to the surface of the silicon). Optionally, the biochip can be washed to remove unbound detector nucleic acid. The hybridized nucleic acid is then detected by any suitable detection means. For example, if the detector nucleic acid is labeled with a fluorescent molecule, the fluorescence can be detected.

In a further embodiment, a nucleic acid complementary for a target nucleotide sequence is contacted with a surface of a silicon biochip of the present invention such that the nucleic acid binds to and becomes immobilized on the silicon. The silicon layer can be prepared so as to have microcavities. The nucleic acid containing sample to be assayed for the presence of one or more target nucleic acid sequences can be provided on the silicon surface in a sol-gel composition. Optionally, the biochip can be washed to remove unbound nucleic acid. The silicon biochip is then contacted with a nucleic acid containing sample to be screened for the presence of the target nucleotide sequence under conditions that permit hybridization of nucleic acids comprising the target nucleotide sequence with the immobilized nucleic acid but that exclude non-specific binding of nucleic acid. Optionally, the biochip can be washed to remove unbound nucleic acid. The hybridized nucleic acid is then detected by any suitable detection means.

In one embodiment, hybridization of nucleic acids is carried out under stringent hybridization conditions. As used herein, "stringent" conditions for hybridization refers to conditions wherein hybridization is typically carried out at about 12 to 25 degrees Celsius (C) below the effective melting temperature (Tm) of the DNA hybrid. The melting temperature, Tm, is described by the following formula (Beltz et al., 1983):

$$Tm=81.5\text{ C}+16.6\text{ Log }[Na^+]+0.41\ (\%\ G+C)-0.61\ (\%\ \text{formamide})-600/\text{length of duplex in base pairs.}$$

Washes can be carried out as follows:

(1) Once or twice at room temperature for 15 minutes in 1×SSPE, 0.1% SDS (low stringency wash); and/or

(2) Once at Tm−20 C for 15 minutes in 0.2×SSPE, 0.1% SDS (moderate stringency wash).

In one embodiment, a nucleic acid, for example, the detector nucleic acid, is labeled with a detectable moiety, such as a fluorescent molecule. Examples of detectable moieties include, but are not limited to, various enzymes, prosthetic groups, fluorescent materials, luminescent materials, bioluminescent materials, and radioactive materials. The detectable substance may be coupled or conjugated either directly to the nucleic acid or indirectly, though an intermediate (such as, for example, a linker known in the art) using techniques known in the art. Examples of suitable enzymes include, but are not limited to, horseradish peroxidase, alkaline phosphatase, beta-galactosidase, or acetylcholinesterase. Examples of suitable prosthetic group complexes include, but are not limited to, streptavidin/biotin and avidin/biotin. Examples of suitable fluorescent materials include, but are not limited to, umbelliferone, fluorescein, fluorescein isothiocyanate, Cascade Blue, rhodamine, dichlorotriazinylamine fluorescein, dansyl chloride, Texas Red, Oregon Green, cyanine (e.g., CY2, CY3, and CY5), allophycocyanine or phycoerythrin. An example of a luminescent material includes luminol. Examples of bioluminescent materials include, but are not limited to, luciferase, luciferin, green fluorescent protein (GFP), enhanced GFP (Yang et al., 1996), and aequorin. Hybridization of the detector nucleic acid is indicative of the presence of the target nucleic acid. In one embodiment, hybridization of the detector nucleic acid to the target nucleic acid is detected using atomic force microscopy (AFM). In another embodiment, hybridization of the detector nucleic acid to the target nucleic acid is detected by detecting the presence of the detectable moiety attached to the detector nucleic acid. In an exemplified embodiment, the detectable moiety is a fluorescent molecule.

In another embodiment, the detector nucleic acid is labeled with a first moiety that can bind to or be bound by a second moiety. In one embodiment, the first moiety is digoxigenin. The digoxigenin molecule can be incorporated into the nucleic acid molecule using digoxigenin conjugated nucleotides (e.g., digoxigenin-dUTP). The digoxigenin molecule can be detected using an antibody that binds to digoxigenin wherein the antibody has a detectable moiety, such as a fluorescent molecule, attached thereto. Alternatively, the antibody bound to digoxigenin can be detected by a second antibody that binds to the antidigoxigenin antibody wherein the second antibody has a detectable moiety, such as a fluorescent molecule, attached thereto. In another embodiment, a biotin-avidin or biotin-streptavidin system can be used. Thus, for example, the nucleic acid can have one or more biotin conjugated nucleotides (e.g., biotin-dUTP) incorporated into it. The biotin moiety can be detected using avidin, streptavidin, or other biotin-binding molecules that have a detectable moiety, such as a fluorescent molecule, attached thereto. Fluorescent molecules contemplated within the scope of the invention include, but are not limited to, umbelliferone, fluorescein, fluorescein isothiocyanate, Cascade Blue, rhodamine, dichlorotriazinylamine fluorescein, dansyl chloride, Texas Red, Oregon Green, cyanine (e.g., CY2, CY3, and CY5), allophycocyanine or phycoerythrin.

The present methods can be used to detect nucleic acid sequences associated with animals, including mammals (e.g., humans), plants, bacteria, viruses, fungi, protozoans, and the like. In one embodiment, the target nucleic acid sequence is from a Respiratory Syncytial Virus (RSV). In an exemplified embodiment, a nucleic acid (SEQ ID NO: 1) derived from RSV was immobilized on a porous silicon biochip of the invention. The biochip was then contacted with a probe or detector nucleic acid (SEQ ID NO: 2) having a sequence complementary to the immobilized nucleic acid (SEQ ID NO: 1) under conditions for selective hybridization of the nucleic acids. The complete genomic sequence of human RSV is known in the art (see, for example, Genbank accession number NC 001781) (SEQ ID NO: 3). Any sequence within SEQ ID NO: 3, or the complement thereof, that is of sufficient length and sequence for selective hybridization to an RSV nucleotide sequence is contemplated for use with the methods and materials of the present invention. Thus, all fragments and variants of the sequence shown in SEQ ID NO: 3, or the complementary sequence of SEQ ID NO: 3, are contemplated for use in the present invention.

Probes or detector nucleic acids of the invention can optionally comprise a detectable label or reporter molecule, such as fluorescent molecules, enzymes, radioactive moiety, and the like. Probes or detector nucleic acids of the invention can be of any suitable length for the method or assay in which they are being employed. Typically, probes or detector nucleic acids of the invention will be 10 to 500 or more nucleotides in length. Probes or detector nucleic acids that are 10 to 20, 21 to 30, 31 to 40, 41 to 50, 51 to 60, 61 to 70, 71 to 80, 81 to 90, 91 to 100, or 101 or more nucleotides in length are contemplated within the scope of the invention. In one

embodiment, probes or detector nucleic acids are any of 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, and so forth up to 100 nucleotides in length. Probes or detector nucleic acids of the invention can have complete (100%) nucleotide sequence identity with the polynucleotide sequence, or the sequence identity can be less than 100%. For example, sequence identity between a probe or detector nucleic acids and a sequence can be 99%, 98%, 97%, 96%, 95%, 90%, 85%, 80%, 75%, 70% or any other percentage sequence identity so long as the probe or detector nucleic acids can hybridize under stringent conditions to a nucleotide sequence of a target nucleic acid.

As used herein, the terms "nucleic acid," "polynucleotide," and "oligonucleotide" refer to a deoxyribonucleotide, ribonucleotide, or a mixed deoxyribonucleotide and ribonucleotide polymer in either single- or double-stranded form, and unless otherwise limited, would encompass known analogs of natural nucleotides that can function in a similar manner as naturally-occurring nucleotides. Polynucleotide sequences include the DNA strand sequence that is transcribed into RNA and the RNA strand that is translated into protein. The complementary sequence of any nucleic acid, polynucleotide, or oligonucleotide of the present invention is also contemplated within the scope of the invention. Polynucleotide sequences also include both full-length sequences as well as shorter sequences derived from the full-length sequences.

The subject invention also concerns variants of the polynucleotides of the present invention, including variants of the RSV sequence shown in SEQ ID NO: 3. Variant sequences include those sequences wherein one or more nucleotides of the sequence have been substituted, deleted, and/or inserted. The nucleotides that can be substituted for natural nucleotides of DNA have a base moiety that can include, but is not limited to, inosine, 5-fluorouracil, 5-bromouracil, hypoxanthine, 1-methylguanine, 5-methylcytosine, and tritylated bases. The sugar moiety of the nucleotide in a sequence can also be modified and includes, but is not limited to, arabinose, xylulose, and hexose. In addition, the adenine, cytosine, guanine, thymine, and uracil bases of the nucleotides can be modified with acetyl, methyl, and/or thio groups. Sequences containing nucleotide substitutions, deletions, and/or insertions can be prepared and tested using standard techniques known in the art.

Polynucleotides contemplated within the scope of the subject invention can also be defined in terms of more particular identity and/or similarity ranges with those sequences of the invention specifically exemplified herein. The sequence identity will typically be greater than 60%, preferably greater than 75%, more preferably greater than 80%, even more preferably greater than 90%, and can be greater than 95%. The identity and/or similarity of a sequence can be 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, or 99% as compared to a sequence exemplified herein. Unless otherwise specified, as used herein percent sequence identity and/or similarity of two sequences can be determined using the algorithm of Karlin and Altschul (1990), modified as in Karlin and Altschul (1993). Such an algorithm is incorporated into the NBLAST and XBLAST programs of Altschul et al. (1990). BLAST searches can be performed with the NBLAST program, score=100, wordlength=12, to obtain sequences with the desired percent sequence identity. To obtain gapped alignments for comparison purposes, Gapped BLAST can be used as described in Altschul et al. (1997). When utilizing BLAST and Gapped BLAST programs, the default parameters of the respective programs (NBLAST and XBLAST) can be used. See NCBI/NIH website.

The subject invention also contemplates those polynucleotide molecules having sequences which are sufficiently homologous with the polynucleotide sequences exemplified herein so as to permit hybridization with that sequence under standard stringent conditions and standard methods (Maniatis et al., 1982).

Biochips of the invention have many advantages, including high responsiveness and selectivity, and are inexpensive. Two primary advantages make nanoscale porous silicon based DNA biochips a very attractive option: (i) enormous surface area, which ranges from about 90 to 783 m^2/cm^3, and which provide numerous sites for potential species to attach and (ii) its room temperature luminescence spans the visible spectrum which makes it an effective transducer. In one embodiment, binding DNA to porous silicon involves coating sol-gel material containing DNA on an oxidized silicon surface. Tetra-ethyl-ortho-silicate (TEOS) can be used to provide a stable coupling between two non-bonding surfaces: an inorganic surface to a bio-molecule (DNA). The most interesting feature of porous silicon is its room temperature visible luminescence. Porous silicon microcavity resonators possess the unique characteristics of line narrowing and luminescence enhancement (Canham, 1990). The emission peak position is completely tunable by modifying the coating over the surface of porous silicon (Lauerhans et al., 1993). The present invention demonstrates the optoelectronics properties of and the compatibility of the porous silicon fabrication process with the usual silicon technology. Further, a mechanical non-fluorescence based approach using AFM technique to detect DNA hybridization can be used with the present invention. In another embodiment, hybridization of sDNA with complementary DNA (cDNA) having a fluorescent probe molecule attached to the cDNA is utilized. Hybridization on the DNA biochip can be detected using photoluminescence technique. Results using a DNA biochip of the present invention and detection techniques are summarized in Tables 1-2. The present invention was found to be more sensitive, economical and time efficient than existing technologies as shown in Table 2.

Any element of any embodiment disclosed herein can be combined with any other element or embodiment disclosed herein as if the combination is explicitly disclosed or exemplified herein, and such combination is contemplated within the scope of the present invention.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

Materials and Methods

Compositions and Reagents.

A crystalline n-type silicon wafer with resistivity ranging between 0.4 and 0.6 Ωcm was used for preparing porous silicon (PS) layers by dipping in a solution of hydrogen fluoride (HF) and ethanol. The target nucleic acid having DNA sequence 3'-GATCCTCGGTAACACAGTACGATACCGTTTTGATTTACATGTCGTAGGTTATTTTTAGCACCTTAGTATTTCTGTAAAAGATTGCCCACGCTAATA-5' (SEQ ID NO: 1) and tetra-ethyl-ortho-silicate (TEOS), HCl, and HNO_3 were contacted with a porous silicon surface (prepared as described herein) for a sufficient period of time to permit the nucleic acid to bind thereto. Then, a detector nucleic acid labeled with

a fluorescent molecule and having the complementary RSV F genome sequence 5'-CTAGGAGCCATTGTGTCATGC-TATGGCAAAACTAAATGTACAGCATC-CAATAAAAATCGTGGAATCATAAAGA-CATTTTCTAACGGGTGCGATTAT-3' (SEQ ID NO: 2) was used for hybridization.

Preparation of Micro Cavities on Silicon Wafer.

With reference to FIG. **1**, anodic etching was used to prepare porous silicon wafers using an electrolyte solution 12 containing 49% high purity aqueous HF and 50% ethanol. A 14.4 cm^2 exposed area of the polished, crystalline n-type silicon wafer 18 with resistivity ranging between 0.4 and 0.6 Ωcm was etched for 5 minutes in a Teflon cell 10 at a constant anodic current of 40.3 mA/cm^2. The cell 10 contains an O-ring 14.

A 200 nm gold layer was deposited by sputtering at the bottom of the silicon wafer 18 to ensure ohmic contact. The cathodic contact was made using a platinum mesh 16 that is in contact with the solution. After the etching process was achieved the wafer was rinsed in ethanol then blown dry in a nitrogen environment. The advantage of this cell geometry is the simplicity of equipment as shown in FIG. **1**. The presence of a difference in the potential between the top and the bottom electrodes of such a cell, leads to different values of the local current density (Jarimaviciute et al., 2003).

Procedure of Immobilization of sDNA onto Porous Silicon.

The method used for binding DNA to the silicon involves coating the oxidized surface of porous silicon with a sol-gel containing single stranded DNA. Sol-gel is a colloidal suspension of silica particles that is gelled to form a solid. The resulting porous gel can be chemically purified and consolidated at high temperatures into high purity silica. The idea behind the sol-gel optical sensors is based on changes of optical parameters of active (sensing) molecules (DNA) physically entrapped in sol-gel thin films. Those changes are induced by changing external physico-chemical parameters such as temperature, hydrostatic pressure or presence of analyte molecules. There are several kinds of optical signals which could be used as analytical response of such sensors, for instance: intensity of light absorbed or emitted by the sensing molecules, time of luminescence decay (Chan, et al., 2000). Non-labeled DNA comprising the nucleotide sequence 3'-GATCCTCGGTAACACAGTACGATAC-CGTTTTGATTTACATGTCGTAGGT-TATTTTTAGCACCTTAGTATTTCTG-TAAAAGATTGCCCACGCTAATA-5' (SEQ ID NO: 1) was immobilized using tetraethylorthosilicate (TEOS) spread over the surface of the silicon wafer to immobilize DNA in the microcavities. A mixture of 25 μL of TEOS, 5 μL of 0.1 M HCl and 204, of de-ionized water (DI) were mixed in a vial (solution A). The last step involved mixing 2 μL single stranded DNA (sDNA) stock solution containing the oligonucleotide (SEQ ID NO: 1) and 3 μL DI water in 5 μL of solution A, resulting in a dilution of solution A to 50%. The pH was controlled near 7 during the mixing procedure described above. The single stranded DNA stock solution contains (1 mg) DNA in 1 mL DI water.

A schematic diagram is shown in FIGS. **2**A-**2**C. FIG. **2**A shows the procedure for immobilizing the sDNA on the porous silicon using TEOS. FIG. **2**B shows the immobilized sDNA on porous silicon and FIG. **2**C shows the hybridization of cDNA that corresponds to RSV F genome having the nucleotide sequence 5'-CTAGGAGCCATTGTGTCATGC-TATGGCAAAACTAAATGTACAGCATC-CAATAAAAATCGTGGAATCATAAAGA-CATTTTCTAACGGGTGCGATTAT-3' (SEQ ID NO: 2). This complementary strand was labeled with a fluorescent molecule.

AFM Characterization of DNA Biochip.

There are various modes of atomic force microscope (AFM) operation, the most common are: Non-contact mode, contact mode, and tapping mode. Tapping mode is the preferred mode of operation in the case of this study since it has features that allow better quality imaging with little deleterious effects on the sample. Analysis of samples in such mode provides higher lateral resolutions, which is critical when analyzing DNA immobilized over a silicon surface. Lower forces and less damage to soft samples make it suitable for DNA structural analysis and sample scraping is virtually eliminated since there are minimal or no lateral forces exerted on the sample. General features of these molecules pertinent to important biological processes are now being characterized using this technique. AFM software is used to obtain quantitative, three-dimensional images of surfaces with ultra-high resolution. AFM provides measurements of surface roughness, grain size, and grain size distribution. All analyses were conducted in air and the samples were brought to room temperature before AFM analysis.

Optical Microscopic Studies of DNA Biochip.

Optical microscopic pictures were recorded for porous silicon wafers and porous silicon containing sDNA and after hybridization of sDNA with cDNA. (FIGS. **4**A-**4**C). The optical microscope of sDNA attached modified single-stranded oligonucleotides were recorded using a Vanox research grade optical microscope for homogeneous hybridization studies. The transverse mode profile for the disk and evanescent field used for sensing is equivalent to that of a slab waveguide with the same thickness and refractive indices. Therefore, one can take advantage of enhanced power at the surface of the porous silicon containing microcavities, having the same penetration depth and relative cladding power as in the straight waveguide structure.

Following are examples which illustrate procedures for practicing the invention. These examples should not be construed as limiting. All percentages are by weight and all solvent mixture proportions are by volume unless otherwise noted.

EXAMPLE 1

Preparation of Porous Silicon Wafer with Immobilized DNA

Porous silicon provides numerous sites for nucleic acid sequence to attach. The porous layer of silicon was fabricated by means of the electrochemical etching in HF solution. FIGS. **4**A-**4**C show the surface of porous silicon after etching. In this case, only a small quantity of charge was generated to generate the pores over the silicon wafer surface. Single strand DNA (sDNA) (SEQ ID NO: 1) of RSV virus was immobilized on PS. A fluorescent probe molecule was attached to a cDNA (SEQ ID NO: 2) having a sequence complementary to the sequence in SEQ ID NO: 1 and then brought into contact with the PS having the sDNA immobilized thereon under conditions sufficient for hybridization of the cDNA to the immobilized sDNA. The fluorescent molecule on the cDNA provides the means of detecting the extent of hybridization of the cDNA to the sDNA.

EXAMPLE 2

SEM Characterization of Microcavities on Silicon Wafer

A cross-section SEM picture of a porous silicon microcavity is shown in FIG. **3**. This picture was taken transversally to

the silicon surface and illustrates hemispherical structures over the entire surface. These structures represent the beginning stage of porous silicon formation. Furthermore, pore depths varying between 0.5 and 0.75 μm are highlighted in the figure by white-dotted lines.

EXAMPLE 3

Optical Microscopy (Epi) Studies of DNA Biochip

Epi indicates incident illumination and has been used in the present invention. The reflection and refraction of light according to the multiple wavelet concepts, now known as the Huygens' principle. When the wavefront encounters the interface between the two media, a portion of the light is reflected and another part is refracted. The periodic rows of miniature semicircular red waves represent the Huygens wavelets that together compose the incident and reflected wave fronts. Wavelets that penetrate the media boundary to become refracted are portrayed in blue, as is the line passing through the center of the refracted beam that denotes their direction of propagation. According to the Huygens model of light, a small portion of each angled wavefront impacts the second medium before the rest of the front reaches the interface. This portion of the wavefront begins to move through the second medium while the rest of the wave is still traveling in the first medium. The speed at which the wavelets travel through is dependent on the refractive indices of the media. If the second medium has a higher refractive index than the first, then the light slows down, and vice versa. Since in either case the wavefront is then traveling at two different speeds, it bends into the second medium, thus changing the angle of propagation. The most common oil-immersion objective in use in routine microscopy is used for magnification of ×100. Fluorescence is a process where a substance after having absorbed light (photons) emits a radiation the wavelength (colour) of which is longer than that of the absorbed light, and where this emission stops immediately after cessation of the excitation. This phenomenon is used to understand the DNA hybridization in DNA biochip. Besides the "classical" excitation of fluorescence in a light microscope it is possible today to obtain the same emission effect. Fluorescence occurs either as autofluorescence of biological and/or inorganic structures or as so called secondary fluorescence after a treatment of the specimen with special dyes (e.g., fluorochromes, fluorescent markers). The microcavity design has an advantage over the single layer structure as the refractive index of the surrounding material increases the reflectivity spectrum to shift. A blue shift is predicted because the pores are filled with sol-gel material with different refractive index as shown in FIGS. **4**A-**4**C. This is further demonstrated during the optical microscopy studies. A optical microscope was used to achieve fluorescence-aided molecule sorting (FAMS) and enabled simultaneous analysis of DNA interactions at the level of a single strand. This was performed by labeling cDNA (SEQ ID NO: 1) corresponding to RSV F genomic sequence. The cDNA probe comprised the nucleotide sequence 5'-CTAGGAGCCATTGTGTCATGCTATGGCAAAACTAAATGTACAGCATCCAATAAAAATCGTGGAATCATAAAGACATTTTCTAACGGGTGCGATTAT-3' (SEQ ID NO: 2) and was used for hybridization. This complementary strand was labeled with a fluorescent molecule that serves as donor-acceptor pair for a Forster resonance energy transfer. FAMS permits equilibrium and kinetic analysis of macromolecule-ligand interactions; this was validated by measuring with sDNA and cDNA. FAMS is a general platform for ratio metric measurements that report on structure, dynamics, stoichiometries, environment, and interactions of diffusing or immobilized molecules, thus enabling detailed mechanistic studies and ultra sensitive diagnostics (Garcia-Parajo et al., 2001).

EXAMPLE 4

UV Studies of DNA Biochip

UV-spectra have shown the retention of the fluorophore in the modified cDNA. The absorbance at 333-340 nm and at 260 nm due to fluorophore and DNA, respectively, and fluorescence emission spectra at 500-520 nm wavelengths clearly confirmed the retention of the chromophore in the oligonucleotides. The relative enhancement in the intensity of peak is due to the fluorescence molecule attached to cDNA. A fluorophore layer placed on top of porous silicon will experience an enhancement of the input optical signal. The effect of field enhancement in microcavities can be interpreted as an increase of absorption efficiency of the fluorophore due to increased interaction length of the incident field with an absorbing molecule. Therefore, an increase in amount of fluorescent photons generated from the molecule at the microcavities versus the linear waveguide is proportional to a number of fluorescence molecule or hybridization with cDNA. Therefore, the advantage of the microcavity format versus waveguide format for analytical applications is the amount of fluorescence molecules present at surface of porous silicon or hybridization. Therefore, the fluorescence signal from the molecules near the microcavity is increased

EXAMPLE 5

AFM Studies of DNA Biochip-AFM Surface Analysis of DNA Immobilized on Microporous Cavity

Surface images of non-hybridized sDNA on PS and sDNA hybridized with an RSV F specific oligonucleotide cDNA probe were taken using a Digital Instruments Atomic Force Microscope (AFM) equipped with nanoscope dimension 3000 software. FIGS. **7**A and **7**B show a two dimensional picture of a section of the microporous silicon wafer with a single strand DNA bundle attached to a cavity. FIGS. **7**A and **7**B show a "horse shoe" like structure coming out of the microcavity.

FIG. **8**A confirms the sDNA bundle shape and provides a better image of the surface profile of the sol gel/sDNA mixture. Further 3D AFM analysis of this image provides more information about the dimensions and the form of the ssDNA bundle, as shown in FIG. **8**A. In FIG. **8**B notice that this value is at least twice as shallow as the value determined by SEM. This is due to the application of the sol gel film which has partially filled the microcavities.

EXAMPLE 6

Photoluminescence Studies of RSV DNA before and after Hybridization

Photoluminescence (PL) was used to study the effectiveness with which the fluorescently tagged RSV oligonucleotide probe molecules hybridize to the fixed sDNA molecules on the surface of the porous silicon. Four samples were selected for this study: two (samples "a" and "b") with sDNA only immobilized on the surface and two hybridized samples having the oligonucleotide probe hybridized to the sDNA

(samples "c" and "d"). All samples were illuminated with a helium cadmium (He Cd) laser at 325 nm and 55 mW. The laser beam was kept at 1.5 mm in diameter to minimize the damage to the DNA molecules. FIG. **9** shows the PL spectra of sDNA fixed on two different "sDNA only" samples (a, b), and two hybridized DNA samples (c, d). A clear increase in the PL intensity was observed after hybridization of the single strand DNA with the RSV cDNA.

FIG. **9** shows that all peaks are found around 505 nm with minor shifting in the wave length in the order of 5 to 10 nm between the sDNA samples and the hybridized ones. However a significant change in the intensity was clearly perceived between sDNA and hybridized DNA samples. While sDNA only samples (a, b) did not show any significant peak, the hybridized (c, d) samples did show two peaks. The smaller peak was registered at 382 nm which corresponds to the color blue. The peak with higher intensity corresponds to the green color with a wavelength of 508 nm. This clearly demonstrates a noticeable change that could be used to quantify the extent of hybridization on the surface. Furthermore, the PL spectra are in concordance with the images obtained by fluorescent microscopy, where bright blue and green areas were observed on the surface of the PS having the cDNA hybridized thereon.

TABLE 1

Fluorescence and optical microscopic studies of DNA biochip.

Technique	sDNA	Hybridized (sDNA: cDNA)
Optical Microscopy	Dark green color was observed with very little fluorescence observed	Bright blue and green fluorescence observed
Mass difference (AFM)	"Horse shoe" like sDNA bundles were found	Hybridized DNA structure with twice the sDNA images were observed
Photoluminescence Studies (PL)	No significant photoluminescence was observed	Relatively high intensity spectra with blue peak (382 nm) and green peak (508 nm)

TABLE 2

Comparison of existing RSV detection techniques with DNA biochip of present invention.

Techniques	Time of detection	Selectivity	Sensitivity	Reference
Radio-immunoassay	Days	Likely to be positive	79%	Meurman et al., 1984a
Immuno-fluorescence (Serology)	Days	Lower background absorbance can be obtained if the RSV antigen is partially purified	75%	Walliver et al., 1980
CF Assays	Days	5-6% sensitivity	25%	Richardson et al., 1978
ELISA	Days	88% selectivity	92%	Meurman, et al. 1984b
DNA Biochip	<Minutes	Highly selective	100%	Present work

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

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We claim:

1. A silicon-based biochip, wherein said biochip comprises a silicon wafer comprising a bottom layer that comprises gold and provides ohmic contact and said biochip further comprises microcavities in said silicon wafer, and wherein a nucleic acid is immobilized on the surface of said silicon wafer and is provided in a sol-gel composition.

2. The biochip according to claim **1**, wherein said nucleic acid is in single stranded form.

3. The biochip according to claim **1**, wherein said biochip is prepared by exposing the surface of a silicon wafer to a solution of hydrofluoric acid (HF) and ethanol and a constant anodic current.

4. The biochip according to claim **1**, wherein said microcavities have a depth of from about 0.5 μm to about 0.75 μm.

5. The biochip according to claim **1**, wherein said nucleic acid is a Respiratory Syncytial Virus (RSV) nucleic acid.

6. The biochip according to claim **5**, wherein said RSV nucleic acid comprises the nucleotide sequence shown in SEQ ID NO:1.

7. The biochip according to claim **5**, wherein said RSV nucleic acid comprises the nucleotide sequence shown in SEQ ID NO:3, or the complement thereof, or said RSV nucleic acid is a fragment of SEQ ID NO:3, or the complement thereof, that is of sufficient length for selective hybridization to an RSV nucleotide sequence.

8. The biochip according to claim **1**, wherein said silicon wafer is a crystalline n-type silicon wafer.

9. The biochip according to claim **1**, wherein said sol-gel composition comprises tetra-ethyl-ortho-silicate (TEOS).

10. The biochip according to claim **1**, wherein said bottom layer is 200 nm in thickness.

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