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(54) **METHODS FOR DROPLET-BASED SAMPLE PREPARATION**

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(57) **ABSTRACT**

This disclosure provides microwell capsule array devices. The microwell capsule array devices are generally capable of performing one or more sample preparation operations. Such sample preparation operations may be used as a prelude to one more or more analysis operations. For example, a device of this disclosure can achieve physical partitioning and discrete mixing of samples with unique molecular identifiers within a single unit in preparation for various analysis operations. The device may be useful in a variety of applications and most notably nucleic-acid-based sequencing, detection and quantification of gene expression and single-cell analysis.

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Co-pending U.S. Appl. No. 15/598,898, filed May 18, 2017.

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Fig. 1A

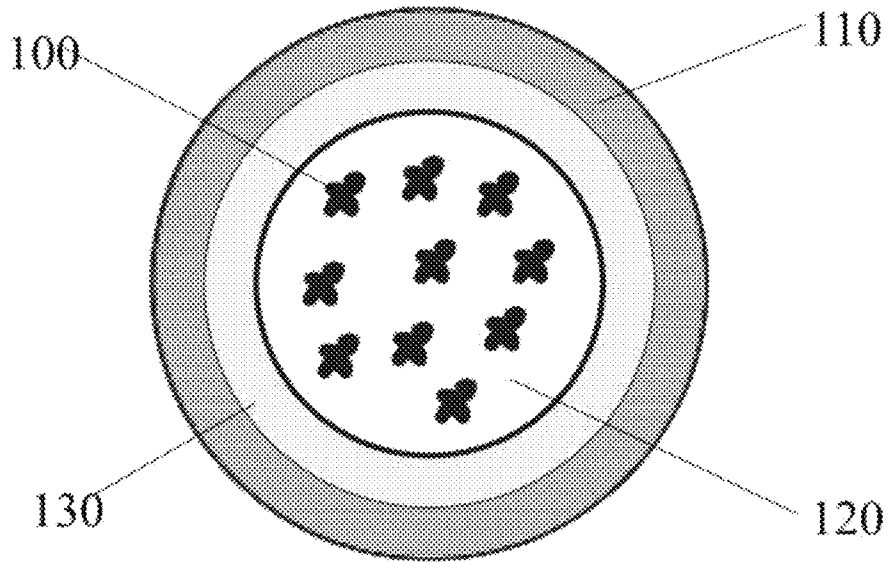


Fig. 1B

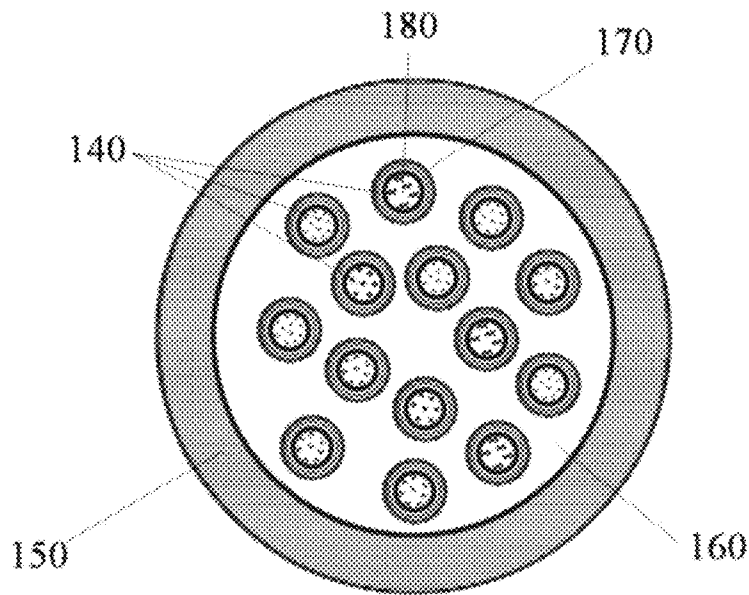


Fig. 2A

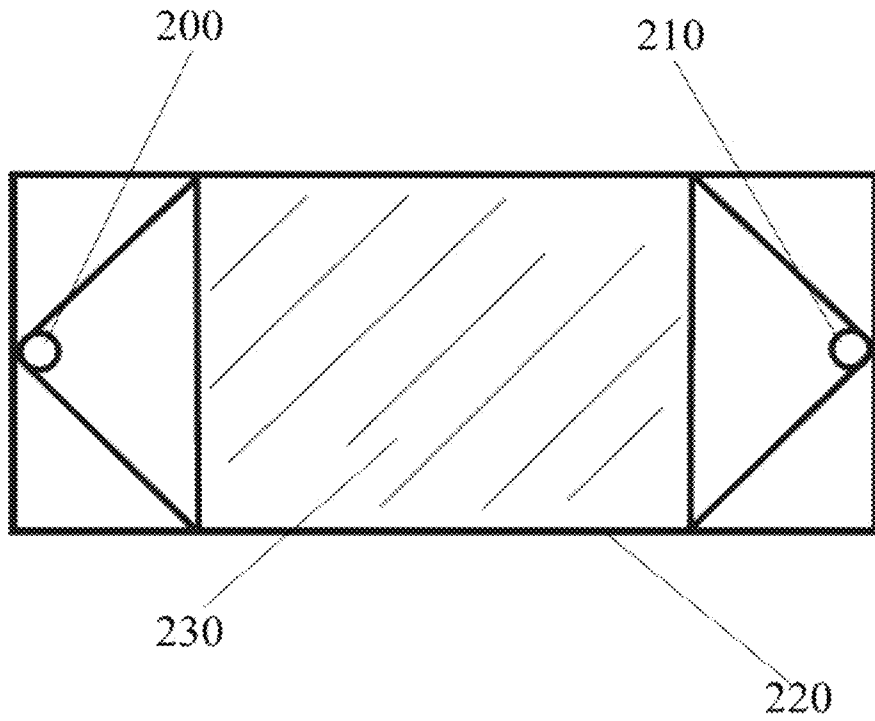


Fig. 2B

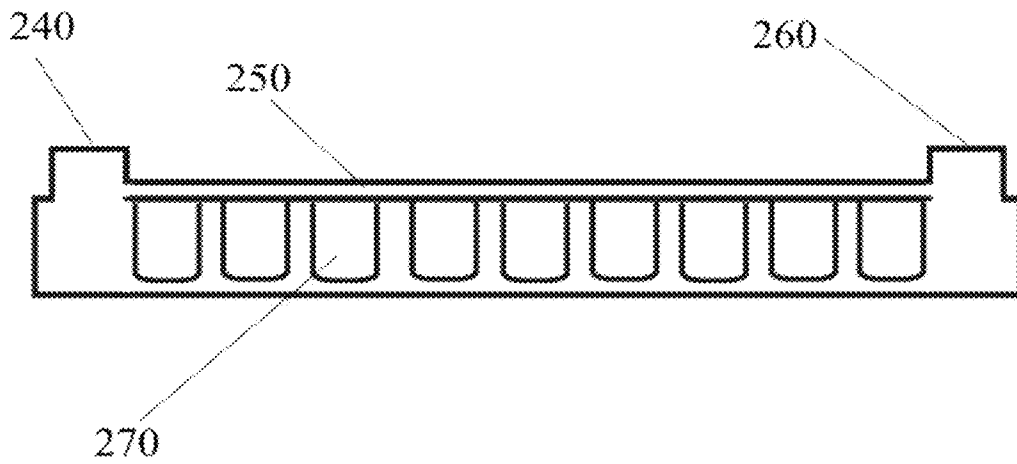


Fig. 3

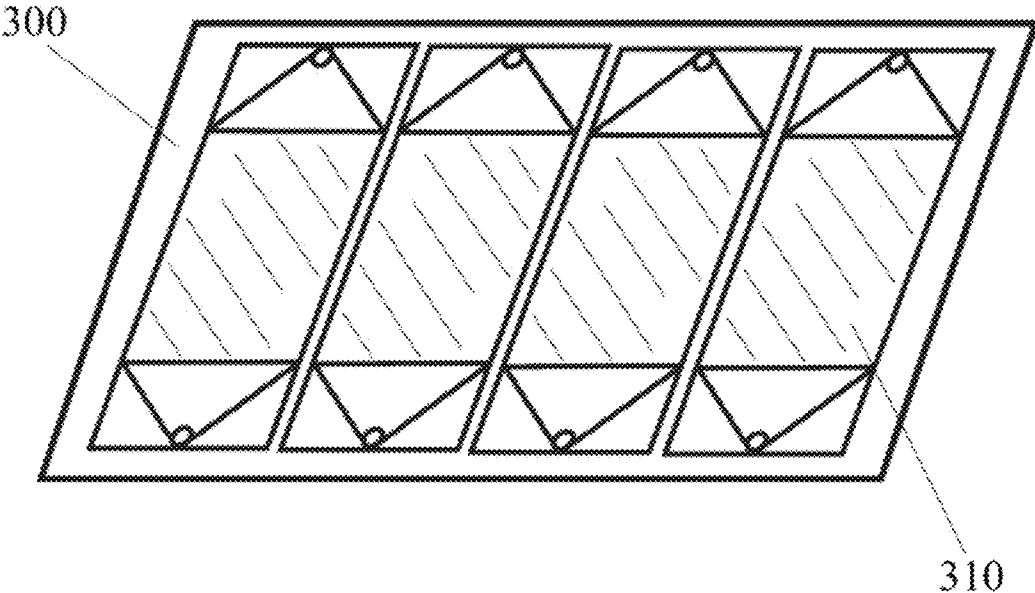


Fig. 4A

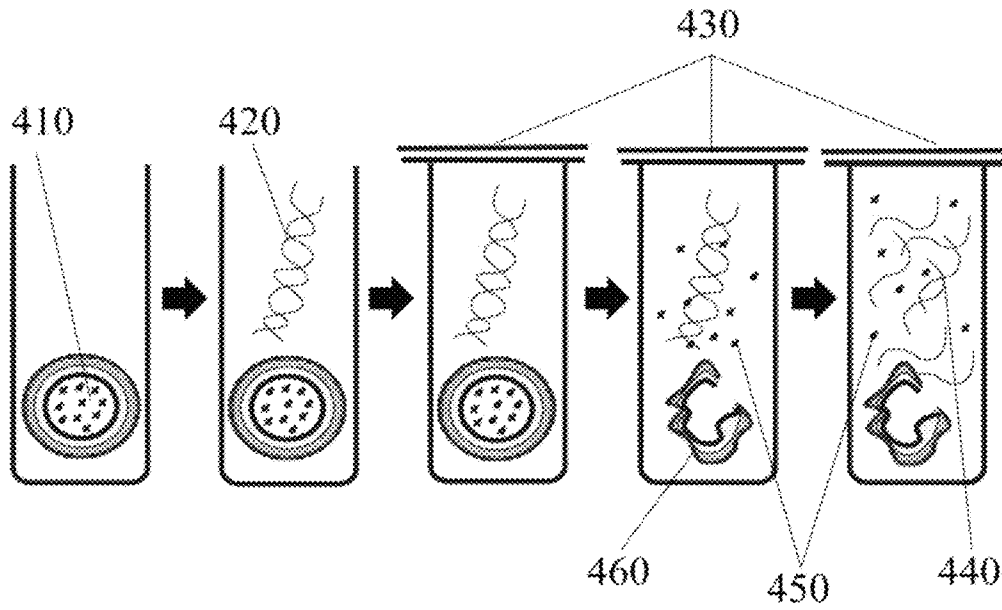
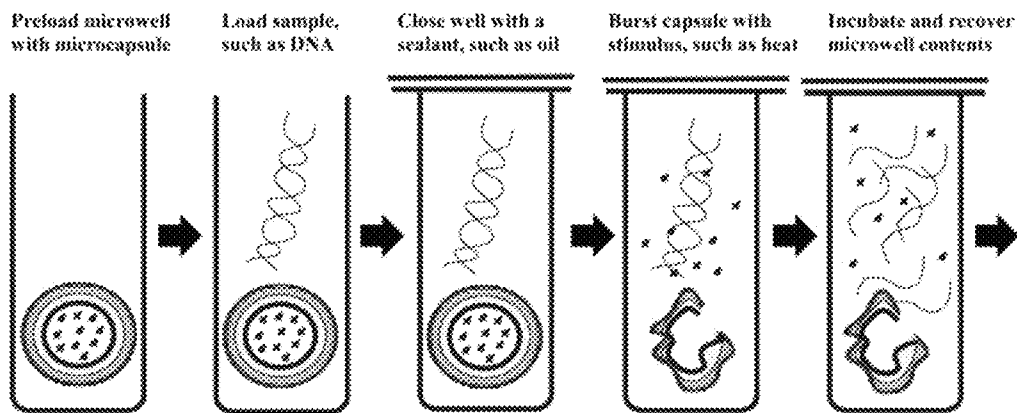


Fig. 4B



METHODS FOR DROPLET-BASED SAMPLE PREPARATION

CROSS-REFERENCE

This application is a continuation of U.S. patent application Ser. No. 13/966,150, filed Aug. 13, 2013, which applications claim the benefit of U.S. Provisional Patent Application No. 61/683,192, filed Aug. 14, 2012; U.S. Provisional Patent Application No. 61/737,374, filed Dec. 14, 2012; U.S. Provisional Patent Application No. 61/762,435, filed Feb. 8, 2013; U.S. Provisional Patent Application No. 61/800,223, filed Mar. 15, 2013; U.S. Provisional Patent Application No. 61/840,403, filed Jun. 27, 2013; and U.S. Provisional Patent Application No. 61/844,804, filed Jul. 10, 2013, which applications are incorporated herein by reference in their entireties for all purposes.

BACKGROUND OF THE INVENTION

The detection and quantification of analytes is important for molecular biology and medical applications such as diagnostics. Genetic testing is particularly useful for a number of diagnostic methods. For example, disorders that are caused by mutations, such as cancer, may be detected or more accurately characterized with DNA sequence information.

Appropriate sample preparation is often needed prior to conducting a molecular reaction such as a sequencing reaction. A starting sample may be a biological sample such as a collection of cells, tissue, or nucleic acids. When the starting material is cells or tissue, the sample may need to be lysed or otherwise manipulated in order to permit the extraction of molecules such as DNA. Sample preparation may also involve fragmenting molecules, isolating molecules, and/or attaching unique identifiers to particular fragments of molecules, among other actions. There is a need in the art for improved methods and devices for preparing samples prior to downstream applications.

SUMMARY OF THE INVENTION

This disclosure provides compositions and methods for a microcapsule array device.

An aspect of the disclosure provides a composition comprising a first microcapsule, wherein: the first microcapsule is degradable upon the application of a stimulus to the first microcapsule; and the first microcapsule comprises an oligonucleotide barcode. In some cases, the first microcapsule may comprise a chemical cross-linker. The chemical cross-linker, for example, may be a disulfide bond. In some cases, the composition may comprise a polymer gel, such as, for example a polyacrylamide gel. The first microcapsule may comprise a bead. In some cases, the bead may be a gel bead.

Moreover, the stimulus may be selected from the group consisting of a biological, chemical, thermal, electrical, magnetic, or photo stimulus, and combination thereof. In some cases, the chemical stimulus may be selected from the group consisting of a change in pH, a change in ion concentration, and a reducing agent. The reducing agent may be, for example, dithiothreitol (DTT) or tris(2-carboxyethyl) phosphine (TCEP).

A second microcapsule may comprise the first microcapsule. Moreover, the second microcapsule may be a droplet. In some cases, the composition may also comprise a nucleic acid that comprises the oligonucleotide barcode, wherein the nucleic acid comprises a deoxyuridine triphosphate (dUTP).

In some cases, the composition may comprise a polymerase unable to accept a deoxyuridine triphosphate (dUTP). Also, the composition may comprise a target analyte, such as, for example, a nucleic acid. The nucleic acid may be selected from the group consisting of DNA, RNA, dNTPs, ddNTPs, amplicons, synthetic nucleotides, synthetic polynucleotides, polynucleotides, oligonucleotides, peptide nucleic acids, cDNA, dsDNA, ssDNA, plasmid DNA, cosmid DNA, High Molecular Weight (MW) DNA, chromosomal DNA, genomic DNA, viral DNA, bacterial DNA, mtDNA (mitochondrial DNA), mRNA, rRNA, tRNA, nRNA, siRNA, snRNA, snoRNA, scaRNA, microRNA, dsRNA, ribozyme, riboswitch and viral RNA. In some cases, the nucleic acid may be genomic DNA (gDNA).

Additionally, the density of the oligonucleotide barcodes may be at least about 1,000,000 oligonucleotide barcodes per the first microcapsule. The oligonucleotide barcode may be coupled to the microcapsule via a chemical cross-linker, such as, for example a disulfide bond.

An additional aspect of the disclosure comprises a device comprising a plurality of partitions, wherein: at least one partition of the plurality of partitions comprises a microcapsule comprising an oligonucleotide barcode; and the microcapsule is degradable upon the application of a stimulus to the microcapsule. The partition, for example, may be a well or a droplet. In some cases, the microcapsule comprises a chemical cross-linker such as, for example, a disulfide bond. Moreover, the microcapsule may comprise a polymer gel such as, for example, a polyacrylamide gel. Also, the microcapsule may comprise a bead. In some cases, the bead may be a gel bead.

The stimulus may be selected from the group consisting of a biological, chemical, thermal, electrical, magnetic, or photo stimulus, and a combination thereof. In some cases, the chemical stimulus may be selected from the group consisting of a change in pH, change in ion concentration, and a reducing agent. The reducing agent, for example, may be dithiothreitol (DTT) or tris(2-carboxyethyl)phosphine (TCEP).

Furthermore, a nucleic acid may comprise the oligonucleotide barcode and the nucleic acid may comprise a deoxyuridine triphosphate (dUTP). In some cases, the partition may comprise a polymerase unable to accept a deoxyuridine triphosphate (dUTP). Additionally, the partition may comprise a target analyte such as, for example, a nucleic acid. The nucleic acid may be selected from the group consisting of DNA, RNA, dNTPs, ddNTPs, amplicons, synthetic nucleotides, synthetic polynucleotides, polynucleotides, oligonucleotides, peptide nucleic acids, cDNA, dsDNA, ssDNA, plasmid DNA, cosmid DNA, High Molecular Weight (MW) DNA, chromosomal DNA, genomic DNA, viral DNA, bacterial DNA, mtDNA (mitochondrial DNA), mRNA, rRNA, tRNA, nRNA, siRNA, snRNA, snoRNA, scaRNA, microRNA, dsRNA, ribozyme, riboswitch and viral RNA. In some cases, the nucleic acid may be genomic DNA (gDNA). The oligonucleotide barcode may be coupled to the microcapsule via a chemical cross-linker. In some cases, the chemical cross-linker may be a disulfide bond.

A further aspect of the disclosure provides a method for sample preparation comprising combining a microcapsule comprising an oligonucleotide barcode and a target analyte into a partition, wherein the microcapsule is degradable upon the application of a stimulus to the microcapsule; and applying the stimulus to the microcapsule to release the oligonucleotide barcode to the target analyte. The partition may be, for example, a well or a droplet. In some cases, the microcapsule may comprise a polymer gel such as, for

example, a polyacrylamide. Moreover, the microcapsule may comprise a bead. In some cases, the bead may be a gel bead. Moreover, the microcapsule may comprise a chemical cross-linker such as, for example, a disulfide bond.

The stimulus may be selected from the group consisting of a biological, chemical, thermal, electrical, magnetic, photo stimulus, and a combination thereof. In some cases, the chemical stimulus may be selected from the group consisting of a change in pH, change in ion concentration, and a reducing agent. The reducing agent may be, for example, dithiothreitol (DTT) or tris(2-carboxyethyl)phosphine (TCEP).

Also, a nucleic acid may comprise the oligonucleotide barcode and the nucleic acid may comprise a deoxyuridine triphosphate (dUTP). In some cases, the partition may comprise a polymerase unable to accept a deoxyuridine triphosphate (dUTP). Moreover, the method may also comprise attaching the oligonucleotide barcode to the target analyte. The attaching may be completed, for example, with a nucleic acid amplification reaction. Moreover, the analyte may be a nucleic acid. In some cases, the nucleic acid may be selected from the group consisting of DNA, RNA, dNTPs, ddNTPs, amplicons, synthetic nucleotides, synthetic polynucleotides, polynucleotides, oligonucleotides, peptide nucleic acids, cDNA, dsDNA, ssDNA, plasmid DNA, cosmid DNA, High Molecular Weight (MW) DNA, chromosomal DNA, genomic DNA, viral DNA, bacterial DNA, mtDNA (mitochondrial DNA), mRNA, rRNA, tRNA, nRNA, siRNA, snRNA, snoRNA, scaRNA, microRNA, dsRNA, ribozyme, riboswitch and viral RNA. In some cases, the nucleic acid may be genomic DNA (gDNA). Furthermore, the oligonucleotide barcode may be coupled to the microcapsule via a chemical cross-linker. In some cases, the chemical cross-linker may be a disulfide bond.

A further aspect of the disclosure provides a composition comprising a degradable gel bead, wherein the gel bead comprises at least about 1,000,000 oligonucleotide barcodes. In some cases, the 1,000,000 oligonucleotide barcodes are identical.

INCORPORATION BY REFERENCE

All publications, patents, and patent applications mentioned in this specification are herein incorporated by reference in their entireties for all purposes and to the same extent as if each individual publication, patent, or patent application was specifically and individually indicated to be incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features of a device of this disclosure are set forth with particularity in the appended claims. A better understanding of the features and advantages of this disclosure will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of a device of this disclosure are utilized, and the accompanying drawings of which:

FIG. 1A is a schematic representation of a microcapsule or inner reagent droplet.

FIG. 1B is a schematic representation of a microcapsule containing multiple inner reagent droplets.

FIG. 2A is a schematic illustration of a top down view of an exemplary microcapsule array.

FIG. 2B is a schematic illustration of an exemplary side view of a microcapsule array.

FIG. 3 is a schematic illustration of a multi-microcapsule array configuration on a 96-well plate holder.

FIG. 4A is a schematic flow diagram representative of a reaction sequence in one microwell of a microwell capsule array.

FIG. 4B is similar to 4A, except that it is annotated with examples of methods that can be performed at each step.

DETAILED DESCRIPTION OF THE INVENTION

While various embodiments of the invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions may occur to those skilled in the art without departing from the invention. It should be understood that various alternatives to the embodiments of the invention described herein may be employed.

I. General Overview

The present disclosure provides microwell or other partition capsule array devices and methods of using such devices. Generally, the device is an assembly of partitions (e.g., microwells, droplets) that are loaded with microcapsules, often at a particular concentration of microcapsules per partition.

The devices may be particularly useful to perform sample preparation operations. In some cases, a device subdivides a sample (e.g., a heterogeneous mixture of nucleic acids, a mixture of cells, etc.) into multiple partitions such that only a portion of the sample is present in each partition. For example, a nucleic acid sample comprising a mixture of nucleic acids may be partitioned such that no more than one strand of (or molecule of) nucleic acid is present in each partition. In other examples, a cell sample may be partitioned such that no more than one cell is present in each partition.

Following the partitioning step, any of a number of different operations may be performed on the subdivided sample within the device. The partitions may include one or more capsules that contain one or more reagents (e.g., enzymes, unique identifiers (e.g., bar codes), antibodies, etc.). In some cases, the device, a companion device or a user provides a trigger that causes the microcapsules to release one or more of the reagents into the respective partition. The release of the reagent may enable contact of the reagent with the subdivided sample. For example, if the reagent is a unique identifier such as a barcode, the sample may be tagged with the unique identifier. The tagged sample may then be used in a downstream application such as a sequencing reaction.

A variety of different reactions and/operations may occur within a device disclosed herein, including but not limited to: sample partitioning, sample isolation, binding reactions, fragmentation (e.g., prior to partitioning or following partitioning), ligation reactions, and other enzymatic reactions. The device also may be useful for a variety of different molecular biology applications including, but not limited to, nucleic acid sequencing, protein sequencing, nucleic acid quantification, sequencing optimization, detecting gene expression, quantifying gene expression, and single-cell analysis of genomic or expressed markers. Moreover, the device has numerous medical applications. For example, it may be used for the identification, detection, diagnosis, treatment, staging of, or risk prediction of various genetic and non-genetic diseases and disorders including cancer.

II. Microcapsules

FIG. 1A is a schematic of an exemplary microcapsule comprising an internal compartment 120 enveloped by a second layer 130, which is encapsulated by a solid or semi-permeable shell or membrane 110. In general, the shell separates the internal compartment(s) from their immediate environment (e.g., interior of a microwell). The internal compartments, e.g., 120, 130, may comprise materials such as reagents. As depicted in FIG. 1A, the reagents 100 may be present in the internal compartment 120. However, in some cases, the reagents are located in the enveloping layer 130 or in both compartments. Generally, the microcapsule may release the inner materials, or a portion thereof, following the introduction of a particular trigger. The trigger may cause disruption of the shell layer 110 and/or the internal enveloping layer 130, thereby permitting contact of the internal compartment 100, 120 with the outside environment, such as the cavity of a microwell.

The microcapsule may comprise several fluidic phases and may comprise an emulsion (e.g. water-in-oil emulsion, oil-in-water emulsion). A microcapsule may comprise an internal layer 120 that is immiscible with a second layer 130 enveloping the internal layer. For example, the internal layer 120 may comprise an aqueous fluid, while the enveloping layer 130 may be a non-aqueous fluid such as an oil. Conversely, the internal layer 120 may comprise a non-aqueous fluid (e.g., oil), and the enveloping layer 130 may comprise an aqueous fluid. In some cases, the microcapsule does not comprise an enveloping second layer. Often, the microcapsule is further encapsulated by a shell layer 110, which may comprise a polymeric material. In some cases, a microcapsule may comprise a droplet.

Droplets and methods for droplet generation, for example, are described in U.S. Pat. No. RE41,780, which is incorporated herein by reference in its entirety for all purposes. The device also may contain a microfluidic element that enables the flow of a sample and/or microcapsules through the device and distribution of the sample and/or microcapsules within the partitions.

The microcapsule can comprise multiple compartments. The microcapsule may comprise at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 50, 100, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000, or 50000 compartments. In other cases, the microcapsule comprises less than 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 50, 100, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000, or 50000 compartments. Similarly, each compartment, or a subset thereof, may also be subdivided into a plurality of additional compartments. In some cases, each compartment, or subset thereof, is subdivided into at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 50, 100, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000, or 50000 compartments. In other cases, each compartment, or subset thereof, is further subdivided into less than 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 50, 100, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000, or 50000 compartments.

There are several possible distributions of reagent in the multiple compartments. For example, each compartment (or some percentage of the total number of compartments) may comprise the same reagent or the same combination or reagents. In some cases, each compartment (or some per-

centage of the total number of compartments) comprises different reagents or a different combination of reagents.

The compartments may be configured in a variety of ways. In some cases, the microcapsule may comprise multiple concentric compartments (repeating units of compartments that contain the preceding compartment), often separated by an immiscible layer. In such microcapsules, the reagents may be present in alternating compartments, in every third compartment, or in every fourth compartment.

In some cases, most of the compartments with a microcapsule are not concentric; instead, they exist as separate, self-contained entities within a microcapsule. FIG. 1B depicts an example of a microcapsule that contains a plurality of smaller microcapsules 140, each containing a reagent. Like many of the other microcapsules described herein, the microcapsule may be encapsulated by an outer shell, often comprising a polymer material 150. The plurality of smaller microcapsules encapsulated within the larger microcapsule may be physically separated by an immiscible fluid 160, thereby preventing mixing of reagents before application of a stimulus and release of reagents into solution. In some cases, the immiscible fluid is loaded with additional materials or reagents. In some cases, the plurality of smaller microcapsules are surrounded by a layer of immiscible fluid (e.g., 170) which is further surrounded by a fluid 160 that is miscible with the inner fluid of the microcapsules. For example, the interior microcapsules 180 may comprise an aqueous interior enveloped by an immiscible (e.g., oil) layer, that is further surrounded by an aqueous layer 160. The miscible compartments (e.g., 160 and 180) may each contain reagents. They may contain the same reagents (or the same combination of reagents) or different reagents (or different combination of reagents). Alternatively, one or some of the miscible compartments may comprise no reagents.

The microcapsule may comprise a polymeric shell (see, e.g., FIGS. 1 and 2) or multiple polymeric shells. For example, the microcapsule may comprise multiple polymeric shells layered on top of each other. In other cases, individual compartments within a microcapsule comprise a polymeric shell, or a subset of the compartments may comprise a polymeric shell. For example, all or some of the smaller compartments 140 in FIG. 1B may comprise a polymeric shell that separates them from the fluidic interior 160. The microcapsule may be designed so that a particular reagent is contained within a compartment that has a polymerized shell, while a different reagent is within a compartment that is simply enveloped by an immiscible liquid. For example, a reagent that is desired to be released upon a heat trigger may be contained within the compartments that have a heat-sensitive or heat-activatable polymerized shell, while reagents designed to be released upon a different trigger may be present in different types of compartments. In another example, paramagnetic particles may be incorporated into the capsule shell wall. A magnet or electric field may then be used to position the capsule to a desired location. In some cases, a magnetic field (e.g., high frequency alternating magnetic field) can be applied to such capsules; the incorporated paramagnetic particles may then transform the energy of the magnetic field into heat, thereby triggering rupture of the capsule.

The microcapsule component of a device of this disclosure may provide for the controlled and/or timed release of reagents for sample preparation of an analyte. Microcapsules may be used in particular for controlled release and transport of varying types of chemicals, ingredients, pharmaceuticals, fragrances etc . . . , including particularly

sensitive reagents such as enzymes and proteins (see, e.g., D. D. Lewis, "Biodegradable Polymers and Drug Delivery Systems", M. Chasin and R. Langer, editors (Marcel Decker, N.Y., 1990); J. P. McGee et al., *J. Control. Release* 34 (1995), 77).

Microcapsules may also provide a means for delivery of reagents in discrete and definable amounts. Microcapsules may be used to prevent premature mixing of reagents with the sample, by segregating the reagents from the sample. Microcapsules also may ease handling of—and limit contacts with—particularly sensitive reagents such as enzymes, nucleic acids and other chemicals used in sample preparation.

A. Preparation of Microcapsules

Microcapsules of a device of this disclosure may be prepared by numerous methods and processes. Preparative techniques may include pan coating, spray drying, centrifugal extrusion, emulsion-based methods, and/or microfluidic techniques. Typically, a method for preparation is chosen based on the desired characteristics of the microcapsule. For example, shell wall thickness, permeability, chemical composition of the shell wall, mechanical integrity of the shell wall and capsule size may be taken into consideration when choosing a method. Methods of preparation may also be selected based on the ability to incorporate specific materials within the capsule such as whether the core materials (e.g., fluids, reagents, etc.) are aqueous, organic or inorganic. Additionally, preparation methods can affect the shape and size of the microcapsule. For example a capsule's shape, (e.g., spherical, ellipsoidal, etc.), may depend on the shape of the droplet in the precursor liquid which may be determined by the viscosity and surface tension of the core liquid, direction of flow of the emulsion, the choice of surfactants used in droplet stabilization, as well as physical confinement such as preparations made in a microchannel or capillary of a particular size (e.g., a size requiring distortion of the microcapsule in order for the microcapsule to fit within the microchannel or capillary).

Microcapsules may be prepared through emulsification polymerization, a process in which monomer units at an aqueous/organic interface in an emulsion polymerize to form a shell. Reagents are mixed with the aqueous phase of the biphasic mixture. Vigorous shaking, or sonication of the mixture, creates droplets containing reagents, which are encased by a polymeric shell.

In some cases, microcapsules may be prepared through layer-by-layer assembly, a process in which negatively and positively charged polyelectrolytes are deposited onto particles such as metal oxide cores. Electrostatic interactions between polyelectrolytes create a polymeric shell around the core. The core can be subsequently removed via addition of acid, resulting in a semi-permeable hollow sphere which can be loaded with various reagents.

In still further cases, microcapsules may be prepared through coacervation, a process in which two oppositely charged polymers in aqueous solution become entangled to form a neutralized polymer shell wall. One polymer may be contained within an oil phase, while the other, of opposite charge is contained in an aqueous phase. This aqueous phase may contain reagents to be encapsulated. The attraction of one polymer for another can result in the formation of coacervates. In some embodiments, gelatin and gum Arabic are components of this preparative method.

Microcapsules also may be prepared through internal phase separation, a process in which a polymer is dissolved in a solvent mixture containing volatile and nonvolatile solvents. Droplets of the resultant solution are suspended in

an aqueous layer, which is stabilized by continual agitation and the use of surfactants. This phase may contain reagents to be encapsulated. When the volatile solvent evaporates, the polymers coalesce to form a shell wall. In some cases, polymers such as polystyrene, poly(methyl methacrylate) and poly(tetrahydrofuran) are used to form shell walls.

Microcapsules also may be prepared through flow focusing methods, a process in which a microcapillary device is used to generate double emulsions containing a single internal droplet encased in a middle fluid which is then dispersed to an outer fluid. The inner droplet may contain reagents to be encapsulated. The middle fluid becomes the shell wall, which can be formed via cross-linking reactions.

B. Microcapsule Composition

Microcapsules may comprise a variety of materials with a wide range of chemical characteristics. Generally, the microcapsules comprise materials with the ability to form microcapsules of a desired shape and size and that are compatible with the reagents to be stored in the microcapsules.

Microcapsules may comprise a wide range of different polymers including but not limited to: polymers, heat sensitive polymers, photosensitive polymers, magnetic polymers, pH sensitive polymers, salt-sensitive polymers, chemically sensitive polymers, polyelectrolytes, polysaccharides, peptides, proteins, and/or plastics. Polymers may include but are not limited to materials such as poly(N-isopropylacrylamide) (PNIPAAm), poly(styrene sulfonate) (PSS), poly(allyl amine) (PAAm), poly(acrylic acid) (PAA), poly(ethylene imine) (PEI), poly(diallyldimethyl-ammonium chloride) (PDADMAC), poly(pyrrrole) (PPy), poly(vinylpyrrolidone) (PVPON), poly(vinyl pyridine) (PVP), poly(methacrylic acid) (PMAA), poly(methyl methacrylate) (PMMA), polystyrene (PS), poly(tetrahydrofuran) (PTHF), poly(phthalaldehyde) (PTHF), poly(hexyl viologen) (PHV), poly(L-lysine) (PLL), poly(L-arginine) (PARG), poly(lactic-co-glycolic acid) (PLGA).

Often, materials for the microcapsules, particularly the shells of microcapsules, may enable the microcapsule to be disrupted with an applied stimulus. For example, a microcapsule may be prepared from heat sensitive polymers and/or may comprise one or more shells comprising such heat-sensitive polymers. The heat-sensitive polymer may be stable under conditions used for storage or loading. Upon exposure to heat, the heat-sensitive polymer components may undergo depolymerization, resulting in disruption to the integrity of the shell and release of the inner materials of the microcapsule (and/or of the inner microcapsules) to the outside environment (e.g., the interior of a microwell). Exemplary heat-sensitive polymers may include, but are not limited to NIPAAm or PNIPAM hydrogel. The microcapsules may also comprise one or more types of oil. Exemplary oils include but are not limited to hydrocarbon oils, fluorinated oils, fluorocarbon oils, silicone oils, mineral oils, vegetable oils, and any other suitable oil.

The microcapsules may also comprise a surfactant, such as an emulsifying surfactant. Exemplary surfactants include, but are not limited to, cationic surfactants, non-ionic surfactants, anionic surfactants, hydrocarbon surfactants or fluorosurfactants. The surfactant may increase the stability of one or more components of the microcapsule, such as an inner compartment that comprises an oil.

Additionally, the microcapsules may comprise an inner material that is miscible with materials external to the capsule. For example, the inner material may be an aqueous fluid and the sample within the microwell may also be in an aqueous fluid. In other examples, the microcapsule may

comprise powders or nanoparticles that are miscible with an aqueous fluid. For example, the microcapsule may comprise such powders or nanoparticles in an inner compartment. Upon disruption of the microcapsule, such powders or nanoparticles are released into the external environment (e.g., interior of microwell) and may mix with an aqueous fluid (e.g., an aqueous sample fluid).

Additionally, the microcapsule may comprise a material that is immiscible with the surrounding environment (e.g., interior of microwell, sample fluid). In such cases, when the inner emulsion is released to the surrounding environment, the phase separation between the inner and outer components may promote mixing, such as mixing of the inner components with the surrounding fluid. In some cases, when a microcapsule is triggered to release its contents, a pressure or force is also released that promotes mixing of internal and external components.

The microcapsules may also comprise a polymer within the interior of the capsule. In some instances this polymer may be a porous polymer bead that may entrap reagents or combinations of reagents. In other instances, this polymer may be a bead that has been previously swollen to create a gel. Examples of polymer based gels that may be used as inner emulsions of capsules may include, but are not limited to sodium alginate gel, or poly acrylamide gel swelled with oligonucleotide bar codes or the like.

In some cases, a microcapsule may be a gel bead comprising any of the polymer based gels described herein. Gel bead microcapsules may be generated, for example, by encapsulating one or more polymeric precursors into droplets. Upon exposure of the polymeric precursors to an accelerator (e.g., tetramethylethylenediamine (TEMED)), a gel bead may be generated.

Analytes and/or reagents, such as oligonucleotide barcodes, for example, may be coupled/immobilized to the interior surface of a gel bead (e.g., the interior accessible via diffusion of an oligonucleotide barcode and/or materials used to generate an oligonucleotide barcode) and/or the outer surface of a gel bead or any other microcapsule described herein. Coupling/immobilization may be via any form of chemical bonding (e.g., covalent bond, ionic bond) or physical phenomena (e.g., Van der Waals forces, dipole-dipole interactions, etc.). In some cases, coupling/immobilization of a reagent to a gel bead or any other microcapsule described herein may be reversible, such as, for example, via a labile moiety (e.g., via a chemical cross-linker, including chemical cross-linkers described herein). Upon application of a stimulus, the labile moiety may be cleaved and the immobilized reagent set free. In some cases, the labile moiety is a disulfide bond. For example, in the case where an oligonucleotide barcode is immobilized to a gel bead via a disulfide bond, exposure of the disulfide bond to a reducing agent can cleave the disulfide bond and free the oligonucleotide barcode from the bead. The labile moiety may be included as part of a gel bead or microcapsule, as part of a chemical linker that links a reagent or analyte to a gel bead or microcapsule, and/or as part of a reagent or analyte.

A gel bead or any other type of microcapsule described herein may contain varied numbers of reagents. The density of a reagent per microcapsule may vary depending on the particular microcapsule utilized and the particular reagent. For example, a microcapsule or gel bead may comprise at least about 1; 10; 100; 1,000; 10,000; 100,000; 1,000,000; 5,000,000; 10,000,000; 50,000,000; 100,000,000; 500,000,000; or 1,000,000,000 oligonucleotide barcodes per micro-

capsule or gel bead. A gel bead may comprise identical oligonucleotide barcodes or may comprise differing oligonucleotide barcodes.

In other example, the microcapsule may comprise one or more materials that create a net neutral, negative or positive charge on the outer shell wall of the capsule. In some instances, the charge of a capsule may aid in preventing or promoting aggregation or clustering of particles, or adherence or repulsion to parts of the device.

In addition, the microcapsule may comprise one or more materials that cause the outer shell wall of the capsule to be hydrophilic or hydrophobic. A hydrophilic material that may be used for capsule shell walls may be poly(N-isopropylacrylamide). A hydrophobic material that may be used for capsule shell walls may be polystyrene. In certain instances, a hydrophilic shell wall may aid in wicking of the capsule into wells comprising aqueous fluid.

C. Microcapsule Size and Shape

A microcapsule may be any of a number of sizes or shapes. In some cases, the shape of the microcapsule may be spherical, ellipsoidal, cylindrical, hexagonal or any other symmetrical or non-symmetrical shape. Any cross-section of the microcapsule may also be of any appropriate shape, include but not limited to: circular, oblong, square, rectangular, hexagonal, or other symmetrical or non-symmetrical shape. In some cases, the microcapsule may be of a specific shape that complements an opening (e.g., surface of a microwell) of the device. For example, the microcapsule may be spherical and the opening of a microwell of the device may be circular.

The microcapsules may be of uniform size (e.g., all of the microcapsules are the same size) or heterogeneous size (e.g., some of the microcapsules are of different sizes). A dimension (e.g., diameter, cross-section, side, etc.) of a microcapsule may be at least about 0.001 μm , 0.01 μm , 0.1 μm , 0.5 μm , 1 μm , 5 μm , 10 μm , 50 μm , 100 μm , 200 μm , 300 μm , 400 μm , 500 μm , 600 μm , 700 μm , 800 μm , 900 μm or 1 nm. In some cases, the microcapsule comprises a microwell that is at most about 0.001 μm , 0.01 μm , 0.1 μm , 0.5 μm , 1 μm , 5 μm , 10 μm , 50 μm , 100 μm , 200 μm , 300 μm , 400 μm , 500 μm , 600 μm , 700 μm , 800 μm , 900 μm or 1 nm.

In some cases, microcapsules are of a size and/or shape so as to allow a limited number of microcapsules to be deposited in individual partitions (e.g., microwells, droplets) of the microcapsule array. Microcapsules may have a specific size and/or shape such that exactly or no more than 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 capsules fit into an individual microwell; in some cases, on average 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 capsules fit into an individual microwell. In still further cases, at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 100, 500, or 1000 capsules fit into an individual microwell.

D. Reagents and Reagent Loading

The devices provided herein may comprise free reagents and/or reagents encapsulated into microcapsules. The reagents may be a variety of molecules, chemicals, particles, and elements suitable for sample preparation reactions of an analyte. For example, a microcapsule used in a sample preparation reaction for DNA sequencing of a target may comprise one or more of the following reagents: enzymes, restriction enzymes (e.g., multiple cutters), ligase, polymerase (e.g., polymerases that do and do not recognize dUTPs and/or uracil), fluorophores, oligonucleotide barcodes, buffers, deoxynucleotide triphosphates (dNTPs) (e.g. deoxyadenosine triphosphate (dATP), deoxycytidine triphosphate (dCTP), deoxyguanosine triphosphate (dGTP), deoxythymidine triphosphate (dTTP), deoxyuridine triphosphate (dUTP)), deoxynucleotide triphosphates (ddNTPs) and the

like. In another example, a microcapsule used in a sample preparation reaction for single cell analysis may comprise reagents such as one or more of the following reagents: lysis buffer, detergent, fluorophores, oligonucleotide barcodes, ligase, proteases, heat activatable proteases, protease or nuclease inhibitors, buffer, enzymes, antibodies, nanoparticles, and the like.

Exemplary reagents include, but are not limited to: buffers, acidic solution, basic solution, temperature-sensitive enzymes, pH-sensitive enzymes, light-sensitive enzymes, metals, metal ions, magnesium chloride, sodium chloride, manganese, aqueous buffer, mild buffer, ionic buffer, inhibitor, enzyme, protein, nucleic acid, antibodies, saccharides, lipid, oil, salt, ion, detergents, ionic detergents, non-ionic detergents, oligonucleotides, nucleotides, dNTPs, ddNTPs, deoxyribonucleic acid (DNA), ribonucleic acid (RNA), peptide nucleic acids, circular DNA (cDNA), double-stranded DNA (dsDNA), single-stranded DNA (ssDNA), plasmid DNA, cosmid DNA, chromosomal DNA, genomic DNA (gDNA), viral DNA, bacterial DNA, mtDNA (mitochondrial DNA), messenger RNA (mRNA), ribosomal RNA (rRNA), transfer RNA (tRNA), nRNA, short-interfering RNA (siRNA), small nuclear RNA (snRNA), small nucleolar RNA (snoRNA), small Cajal body specific RNA, (scaRNA), microRNA, double-stranded RNA (dsRNA), ribozyme, riboswitch and viral RNA, polymerase (e.g., polymerases that do and do not recognize dUTPs and/or uracil), ligase, restriction enzymes, proteases, nucleases, protease inhibitors, nuclease inhibitors, chelating agents, reducing agents (e.g., dithiothreitol (DTT), 2-tris(2-carboxyethyl)phosphine (TCEP)), oxidizing agents, fluorophores, probes, chromophores, dyes, organics, emulsifiers, surfactants, stabilizers, polymers, water, small molecules, pharmaceuticals, radioactive molecules, preservatives, antibiotics, aptamers, and pharmaceutical drug compounds.

In some cases, a microcapsule comprises a set of reagents that have a similar attribute (e.g., a set of enzymes, a set of minerals, a set of oligonucleotides, a mixture of different bar-codes, a mixture of identical bar-codes). In other cases, a microcapsule comprises a heterogeneous mixture of reagents. In some cases, the heterogeneous mixture of reagents comprises all components necessary to perform a reaction. In some cases, such mixture comprises all components necessary to perform a reaction, except for 1, 2, 3, 4, 5, or more components necessary to perform a reaction. In some cases, such additional components are contained within a different microcapsule or within a solution within a partition (e.g., microwell) of the device.

Reagents may be pre-loaded into the device (e.g., prior to introduction of analyte) or post-loaded into the device. They may be loaded directly into the device; or, in some cases, the reagents are encapsulated into a microcapsule that is loaded into the device. In some cases, only microcapsules comprising reagents are introduced. In other cases, both free reagents and reagents encapsulated in microcapsules are loaded into the device, either sequentially or concurrently. In some cases, reagents are introduced to the device either before or after a particular step. For example, a lysis buffer reagent may be introduced to the device following partitioning of a cellular sample into multiple partitions (e.g., microwells, droplets) within the device. In some cases, reagents and/or microcapsules comprising reagents are introduced sequentially such that different reactions or operations occur at different steps. The reagents (or microcapsules) may be also be loaded at steps interspersed with a reaction or operation step. For example, microcapsules comprising reagents for fragmenting molecules (e.g.,

nucleic acids) may be loaded into the device, followed by a fragmentation step, which may be followed by loading of microcapsules comprising reagents for ligating bar-codes (or other unique identifiers, e.g., antibodies) and subsequent ligation of the bar-codes to the fragmented molecules. Additional methods of loading reagents are described further herein in other sections.

E. Molecular 'Barcodes'

It may be desirable to retain the option of identifying and tracking individual molecules or analytes after or during sample preparation. In some cases, one or more unique molecular identifiers, sometimes known in the art as a 'molecular barcodes,' are used as sample preparation reagents. These molecules may comprise a variety of different forms such as oligonucleotide bar codes, antibodies or antibody fragments, fluorophores, nanoparticles, and other elements or combinations thereof. Depending upon the specific application, molecular barcodes may reversibly or irreversibly bind to the target analyte and allow for identification and/or quantification of individual analytes after recovery from a device after sample preparation.

A device of this disclosure may be applicable to nucleic acid sequencing, protein detection, single molecule analysis and other methods that require a) precise measurement of the presence and amount of a specific analyte b) multiplex reactions in which multiple analytes are pooled for analysis. A device of this disclosure may utilize the microwells of the microwell array or other type of partition (e.g., droplets) to physically partition target analytes. This physical partitioning allows for individual analytes to acquire one or more molecular barcodes. After sample preparation, individual analytes may be pooled or combined and extracted from a device for multiplex analysis. For most applications, multiplex analysis substantially decreases the cost of analysis as well as increases through-put of the process, such as in the case of the nucleic acid sequencing. Molecular barcodes may allow for the identification and quantification of individual molecules even after pooling of a plurality of analytes. For example, with respect to nucleic acid sequencing, molecular barcodes may permit the sequencing of individual nucleic acids, even after the pooling of a plurality of different nucleic acids.

Oligonucleotide barcodes, in some cases, may be particularly useful in nucleic acid sequencing. In general, an oligonucleotide barcode may comprise a unique sequence (e.g., a barcode sequence) that gives the oligonucleotide barcode its identifying functionality. The unique sequence may be random or non-random. Attachment of the barcode sequence to a nucleic acid of interest may associate the barcode sequence with the nucleic acid of interest. The barcode may then be used to identify the nucleic acid of interest during sequencing, even when other nucleic acids of interest (e.g., comprising different barcodes) are present. In cases where a nucleic acid of interest is fragmented prior to sequencing, an attached barcode may be used to identify fragments as belonging to the nucleic acid of interest during sequencing.

An oligonucleotide barcode may consist solely of a unique barcode sequence or may be included as part of an oligonucleotide of longer sequence length. Such an oligonucleotide may be an adaptor required for a particular sequencing chemistry and/or method. For example, such adaptors may include, in addition to an oligonucleotide barcode, immobilization sequence regions necessary to immobilize (e.g., via hybridization) the adaptor to a solid surface (e.g., solid surfaces in a sequencer flow cell channel); sequence regions required for the binding of sequenc-

ing primers; and/or a random sequence (e.g., a random N-mer) that may be useful, for example, in random amplification schemes. An adaptor can be attached to a nucleic acid to be sequenced, for example, by amplification, ligation, or any other method described herein.

Moreover, an oligonucleotide barcode, and/or a larger oligonucleotide comprising an oligonucleotide barcode may comprise natural nucleic acid bases and/or may comprise non-natural bases. For example, in cases where an oligonucleotide barcode or a larger oligonucleotide comprising an oligonucleotide barcode is DNA, the oligonucleotide may comprise the natural DNA bases adenine, guanine, cytosine, and thymine and/or may comprise non-natural bases such as uracil.

F. Microcapsule-Preparation for Microwell Loading

Following preparation, reagent loaded microcapsules may be loaded into a device using a variety of methods. Microcapsules, in some instances, may be loaded as 'dry capsules.' After preparation, capsules may be separated from a liquid phase using various techniques, including but not limited to differential centrifugation, evaporation of the liquid phase, chromatography, filtration and the like. 'Dry capsules' may be collected as a powder or particulate matter and then deposited into microwells of the microwell array. Loading 'dry capsules' may be a preferred method in instances in which loading of 'wet capsules,' leads to inefficiencies of loading such as empty wells and poor distribution of microcapsules across the microwell array.

Reagent-loaded microcapsules may also be loaded into a device when the microcapsules are within a liquid phase, and thereby loaded as 'wet capsules.' In some instances, microcapsules may be suspended in a volatile oil such that the oil can be removed or evaporated, leaving only the dry capsule in the well. Loading 'wet capsules' may be a preferred method in some instances in which loading of dry capsules leads to inefficiencies of loading, such as microcapsule clustering, aggregation and poor distribution of microcapsules across the microwell array. Additional methods of loading reagents and microcapsules are described in other sections of this disclosure.

The microcapsules also may have a particular density. In some cases, the microcapsules are less dense than an aqueous fluid (e.g., water); in some cases, the microcapsules are denser than an aqueous fluid (e.g., water). In some cases, the microcapsules are less dense than a non-aqueous fluid (e.g., oil); in some cases, the microcapsules are denser than a non-aqueous fluid (e.g., oil). Microcapsules may comprise a density at least about 0.05 g/cm³, 0.1 g/cm³, 0.2 g/cm³, 0.3 g/cm³, 0.4 g/cm³, 0.5 g/cm³, 0.6 g/cm³, 0.7 g/cm³, 0.8 g/cm³, 0.81 g/cm³, 0.82 g/cm³, 0.83 g/cm³, 0.84 g/cm³, 0.85 g/cm³, 0.86 g/cm³, 0.87 g/cm³, 0.88 g/cm³, 0.89 g/cm³, 0.90 g/cm³, 0.91 g/cm³, 0.92 g/cm³, 0.93 g/cm³, 0.94 g/cm³, 0.95 g/cm³, 0.96 g/cm³, 0.97 g/cm³, 0.98 g/cm³, 0.99 g/cm³, 1.00 g/cm³, 1.05 g/cm³, 1.1 g/cm³, 1.2 g/cm³, 1.3 g/cm³, 1.4 g/cm³, 1.5 g/cm³, 1.6 g/cm³, 1.7 g/cm³, 1.8 g/cm³, 1.9 g/cm³, 2.0 g/cm³, 2.1 g/cm³, 2.2 g/cm³, 2.3 g/cm³, 2.4 g/cm³, or 2.5 g/cm³. In other cases, microcapsule densities may be at most about 0.7 g/cm³, 0.8 g/cm³, 0.81 g/cm³, 0.82 g/cm³, 0.83 g/cm³, 0.84 g/cm³, 0.85 g/cm³, 0.86 g/cm³, 0.87 g/cm³, 0.88 g/cm³, 0.89 g/cm³, 0.90 g/cm³, 0.91 g/cm³, 0.92 g/cm³, 0.93 g/cm³, 0.94 g/cm³, 0.95 g/cm³, 0.96 g/cm³, 0.97 g/cm³, 0.98 g/cm³, 0.99 g/cm³, 1.00 g/cm³, 1.05 g/cm³, 1.1 g/cm³, 1.2 g/cm³, 1.3 g/cm³, 1.4 g/cm³, 1.5 g/cm³, 1.6 g/cm³, 1.7 g/cm³, 1.8 g/cm³, 1.9 g/cm³, 2.0 g/cm³, 2.1 g/cm³, 2.2 g/cm³, 2.3 g/cm³, 2.4 g/cm³, or 2.5 g/cm³. Such densities can reflect the density of the microcapsule in any particular fluid (e.g., aqueous, water, oil, etc.)

III. Microwell Array

A. Structure/Features

A device of this disclosure may be a microwell array comprising a solid plate containing a plurality of holes, cavities or microwells in which microcapsules and/or analytes are deposited. Generally, a fluidic sample (or analyte) is introduced into the device (e.g., through an inlet) and then travels through a flow channel which distributes the sample into multiple microwells. In some cases, additional fluid is introduced into the device as well. The microwells may comprise microcapsules when the sample is introduced; or, in some cases, the microcapsules are introduced into the microwells following introduction of the sample.

FIG. 2A depicts a prototype microwell array; a sideview is depicted in FIG. 2B. The microwell array may include a plate 220 that can be made of any suitable material commonly used in a chemical laboratory, including fused silica, soda lime glass, borosilicate glass, PMMA, sapphire, silicon, germanium, cyclic olefin copolymer and cyclic polymer, polyethylenes, polypropylenes, polyacrylates, polycarbonates, plastics, Topas, and other suitable substrates known in the art. The plate 220 may initially be a flat solid plate comprising a regular pattern of microwells 270. The microwells may be formed by drilling or chemical dissolution or any other suitable method of machining; however, plates with a desired hole pattern are preferably molded, e.g. by injection-molding, embossing, or using a suitable polymer, such as cyclic olefin copolymer.

The microwell array may comprise an inlet (200 and 240) and/or an outlet (210 and 260); in some cases, the microwell array comprises multiple inlets and/or outlets. A sample (or analyte) or microcapsules may be introduced to the device via the inlet. Solutions containing analytes, reagents and/or microcapsules may be manually applied to the inlet port 200 and 240 (or to a conduit attached to the inlet port) via a pipette. In some cases, a liquid handling device is used to introduce analytes, reagents, and/or microcapsules to the device. Exemplary liquid handling devices may rely on a pipetting robot, capillary action, or dipping into a fluid. In some cases, the inlet port is connected to a reservoir comprising microcapsules or analytes. The inlet port may be attached to a flow channel 250 that permits distribution of the analyte, sample, or microcapsules to the microwells in the device. In some cases, the inlet port may be used to introduce to the device a fluid (e.g., oil, aqueous) that does not contain microcapsules or analyte, such as a carrier fluid. The carrier fluid may be introduced via the inlet port before, during, or following the introduction of analyte and/or microcapsules. In cases where the device has multiple inlets, the same sample may be introduced via the multiple inlets, or each inlet may convey a different sample. In some cases, one inlet may convey a sample or analyte to the microwells, while a different inlet conveys free reagents and/or reagents encapsulated in microcapsules to the device. The device may have at least 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 inlets and/or outlets.

In some cases, solutions containing microcapsules and/or analytes may be pulled through the device via a vacuum manifold attached to the outlet port 210 and 260. Such manifold may apply a negative pressure to the device. In other cases, a positive pressure is used to move sample, analytes, and/or microcapsules through the device. The area, length, and width of surfaces of 230 according to this disclosure may be varied according to the requirements of the assay to be performed. Considerations may include, for example, ease of handling, limitations of the material(s) of which the surface is formed, requirements of detection or processing systems, requirements of deposition systems

(e.g. microfluidic systems), and the like. The thickness may comprise a thickness of at least about 0.001 mm, 0.005 mm, 0.01 mm, 0.05 mm, 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm, 0.8 mm, 0.9 mm, 1.0 mm, 2.0 mm, 3.0 mm, 4.0 mm, 5.0 mm, 6.0 mm, 7.0 mm, 8.0 mm, 9.0 mm, 10.0 mm, 11 mm, 12 mm, 13 mm, 14 mm, or 15 mm. In other cases, microcapsule thickness may be at most 0.001 mm, 0.005 mm, 0.01 mm, 0.05 mm, 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm, 0.8 mm, 0.9 mm, 1.0 mm, 2.0 mm, 3.0 mm, 4.0 mm, 5.0 mm, 6.0 mm, 7.0 mm, 8.0 mm, 9.0 mm, 10.0 mm, 11 mm, 12 mm, 13 mm, 14 mm, or 15 mm.

The microwells 270 can be any shape and size suitable for the assay performed. The cross-section of the microwells may have a cross-sectional dimension that is circular, rectangular, square, hexagonal, or other symmetric or non-symmetric shape. In some cases, the shape of the microwell may be cylindrical, cubic, conical, frustoconical, hexagonal or other symmetric or non-symmetric shape. The diameter of the microwells 270 may be determined by the size of the wells desired and the available surface area of the plate itself. Exemplary microwells comprise diameters of at least 0.01 μm , 0.1 μm , 0.2 μm , 0.3 μm , 0.4 μm , 0.5 μm , 1 μm , 10 μm , 25 μm , 50 μm , 75 μm , 100 μm , 200 μm , 300 μm , 400 μm , 500 μm , 600 μm , 700 μm , 800 μm , 900 μm , 1.0 mm. In other cases, microwell diameters may comprise at most 0.01 μm , 0.1 μm , 0.2 μm , 0.3 μm , 0.4 μm , 0.5 μm , 1 μm , 10 μm , 25 μm , 50 μm , 75 μm , 100 μm , 200 μm , 300 μm , 400 μm , 500 μm , 600 μm , 700 μm , 800 μm , 900 μm or 1.0 mm.

The capacity (or volume) of each well can be a measure of the height of the well (the thickness of the plate) and the effective diameter of each well. The capacity of an individual well may be selected from a wide range of volumes. In some cases, the device may comprise a well (or microwell) with a capacity of at least 0.001 fL, 0.01 fL, 0.1 fL, 0.5 fL, 1 fL, 5 fL, 10 fL, 50 fL, 100 fL, 200 fL, 300 fL, 400 fL, 500 fL, 600 fL, 700 fL, 800 fL, 900 fL, 1 pL, 5 pL, 10 pL, 50 pL, 100 pL, 200 pL, 300 pL, 400 pL, 500 pL, 600 pL, 700 pL, 800 pL, 900 pL, 1 nL, 5 nL, 10 nL, 50 nL, 100 nL, 200 nL, 300 nL, 400 nL, 500 nL, 1 μL , 5 μL , 10 μL , 50 μL , or 100 μL . In other cases, the microcapsule comprises a microwell that is less than 0.001 fL, 0.01 fL, 0.1 fL, 0.5 L, 5 fL, 10 fL, 50 fL, 100 fL, 200 fL, 300 fL, 400 fL, 500 fL, 600 fL, 700 fL, 800 fL, 900 fL, 1 pL, 5 pL, 10 pL, 50 pL, 100 pL, 200 pL, 300 pL, 400 pL, 500 pL, 600 pL, 700 pL, 800 pL, 900 pL, 1 nL, 5 nL, 10 nL, 50 nL, 100 nL, 200 nL, 300 nL, 400 nL, 500 nL, 1 μL , 5 μL , or 100 μL .

There may be variability in the volume of fluid in different microwells in the array. More specifically, the volume of different microwells may vary by at least (or at most) plus or minus 1%, 2%, 3%, 4%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 200%, 300%, 400%, 500%, or 1000% across a set of microwells. For example, a microwell may comprise a volume of fluid that is at most 80% of the fluid volume within a second microwell.

Based on the dimension of individual microwells and the size of the plate, the microwell array may comprise a range of well densities. In some examples, a plurality of microwells may have a density of at least about 2,500 wells/cm², at least about 1,000 wells/cm². In some cases, the plurality of wells may have a density of at least 10 wells/cm². In other cases, the well density may comprise at least 10 wells/cm², 50 wells/cm², 100 wells/cm², 500 wells/cm², 1000 wells/cm², 5000 wells/cm², 10000 wells/cm², 50000 wells/cm², or 100000 wells/cm². In other cases, the well density may be less than 100000 wells/cm², 10000 wells/cm², 5000 wells/cm², 1000 wells/cm², 500 wells/cm², or 100 wells/cm².

In some cases, the interior surface of the microwells comprises a hydrophilic material that preferably accommodates an aqueous sample; in some cases, the region between the microwells is composed of a hydrophobic material that may preferentially attract a hydrophobic sealing fluid described herein.

Multiple microwell arrays, e.g., FIG. 2B may be arranged within a single device. FIG. 3, 300. For example, discrete microwell array slides may be arrayed in parallel on a plate holder. In some cases, at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 25, 50 or 100 microwell arrays are arrayed in parallel. In other cases, at most 100, 50, 25, 10, 9, 8, 7, 6, 5, 4, 3, 2 or 1 devices are arrayed in parallel. The microwell arrays within a common device may be manipulated simultaneously or sequentially. For example, arrayed devices may be loaded with samples or capsules simultaneously or sequentially.

B. Microwell Array Fluids

The microwell array may comprise any of a number of different fluids including aqueous, non-aqueous, oils, and organic solvents, such as alcohols. In some cases, the fluid is used to carry a component, e.g., reagent, microcapsule, or analyte, to a target location such as microwells, output port, etc. In other cases, the fluid is used to flush the system. In still other cases, the fluid may be used to seal the microwells.

Any fluid or buffer that is physiologically compatible with the analytes (e.g., cells, molecules) or reagents used in the device may be used. In some cases, the fluid is aqueous (buffered or not buffered). For example, a sample comprising a population of cells suspended in a buffered aqueous solution may be introduced into the microwell array, allowed to flow through the device, and distributed to the microwells. In other cases, the fluid passing through the device is nonaqueous (e.g., oil). Exemplary non-aqueous fluids include but are not limited to: oils, non-polar solvent, hydrocarbon oil, decane (e.g., tetradecane or hexadecane), fluorocarbon oil, fluorinated oil, silicone oil, mineral oil, or other oil.

Often, the microcapsules are suspended in a fluid that is compatible with the components of the shell of the microcapsule. Fluids including but not limited to water, alcohols, hydrocarbon oils or fluorocarbon oils are particularly useful fluids for suspending and flowing microcapsules through the microarray device.

C. Further Partitioning and Sealing

After the analyte, free reagents, and/or microcapsules are loaded into the device and distributed to the microwells, a sealing fluid may be used to further partition or isolate them within the microwells. The sealing fluid may also be used to seal the individual wells. The sealing fluid may be introduced through the same inlet port that was used to introduce the analyte, reagents and/or microcapsules. But in some cases, the sealing fluid is introduced to the device by a separate inlet port, or through multiple separate inlet ports.

Often, the sealing fluid is a non-aqueous fluid (e.g., oil). When the sealing fluid flows through the microwell array device, it may displace excess aqueous solution (e.g., solution comprising analytes, free reagents and/or microcapsules) from individual microwells, thereby potentially removing aqueous bridges between adjacent microwells. The wells themselves, as described herein, may comprise a hydrophilic material that enables wicking of the aqueous fluids (e.g., sample fluid, microcapsule fluid) into individual wells. In some cases, regions external to the wells comprise hydrophobic material, again to encourage the positioning of the aqueous fluid into the interior of the microwells.

The sealing fluid may either remain in the device or be removed. The sealing fluid may be removed, e.g., by flowing

through the outlet port. In other cases, the sealing oil may comprise a volatile oil that can be removed by the application of heat. Once the sealing fluid is removed, analytes, free reagents and/or microcapsules may be physically partitioned from one another in the microwells.

A fluid may be selected such that its density is equal to, greater than or less than the density of the microcapsules. For example, the microcapsules may be denser than the sealing oil and/or aqueous fluid of the sample and reagents, thereby enabling the microcapsules to remain in the microwells as the sealing oil flows through the device. In another example, the capsules may be less dense than the aqueous fluid of the sample or the fluid that the microcapsules are suspended in, as described herein, thereby facilitating movement and distribution of the capsules across the plurality of microwells in a device.

In the case of microcapsules comprising paramagnetic material, a magnetic field may be used to load or direct the capsules into the microwells. A magnetic field may also be used to retain such microcapsules within the wells while the wells are being filled with sample, reagent, and/or sealing fluids. The magnetic field may also be used to remove capsule shells from the wells, particularly following rupture of the capsules.

In some cases, the sealing fluid may remain in the microwells when operations or reactions are conducted therein. The presence of the sealing fluid may act to further partition, isolate, or seal the individual microwells. In other cases, the sealing fluid may act as a carrier for the microcapsules. For example, sealing fluid comprising microcapsules may be introduced to the device to facilitate distribution of the microcapsules to the individual microwells. For such applications, the sealing fluid may be denser than the microcapsules in order to encourage more even distribution of the microcapsules to the microwells. Upon application of a stimulus, the microcapsules within the sealing fluid may release reagents to the microwell. In some cases, the sealing fluid may comprise a chemical or other agent capable of traveling from the sealing fluid to a well (e.g., by leaching or other mechanism) and triggering capsule rupture, where the capsule is present within the microwell or within the sealing fluid.

Methods other than those involving sealing fluids may also be used to seal the microwells following the loading of the analyte, free reagents, and/or microcapsules. For example, the microwells may be sealed with a laminate, tape, plastic cover, oils, waxes, or other suitable material to create an enclosed reaction chamber. The sealants described herein may protect the contents of the microwells from evaporation or other unintended consequences of the reactions or operations. Prevention of evaporation may be particularly necessary when heat is applied to the device, e.g., when heat is applied to stimulate microcapsule release.

In some cases, the laminate seal may also allow recovery of contents from individual wells. In this case, a single well of interest may be unsealed (e.g., by removal of the laminate seal) at a given time in order to enable further analysis of an analyte such as by MALDI mass spectrometry. Such applications may be useful in a number of settings, including high-throughput drug screening.

III. Loading Step(s)

As described herein, analytes, free reagents, and/or microcapsules may be loaded into the present device in any appropriate manner or order. The loading may be random or non-random. In some cases, a precise number of analytes and/or microcapsules are loaded into each individual microwell. In some cases, a precise number of analytes

and/or microcapsules are loaded into a particular subset of microwells in the plate. In still other cases, an average number of analytes and/or microcapsules are loaded into each individual microwell. Furthermore, as described herein, in some cases, "dry" microcapsules are loaded into the device, while in other cases "wet" microcapsules are loaded into the device. In some cases, a combination of "dry" and "wet" microcapsules and/or reagents are loaded into the device, either simultaneously or sequentially.

As mentioned herein, the loading of the device may occur in any order and may occur in multiple stages. In some cases, the microcapsules are pre-loaded into the device, prior to the loading of the analyte. In other cases, the microcapsules and analyte are loaded concurrently. In still other cases, the analytes are loaded before the microcapsules are loaded.

The microcapsules and/or analytes may be loaded in multiple stages or multiple times. For example, microcapsules may be loaded into the device both prior to and after analytes are loaded into the device. The microcapsules that are pre-loaded (e.g., loaded prior to the analyte introduction) may comprise the same reagents as the microcapsules loaded after the analyte introduction. In other cases, the pre-loaded microcapsules contain reagents that are different from the reagents within the microcapsules loaded after analyte introduction. In some cases, at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, or 20 different sets of microcapsules are loaded onto the device. In some cases, the different sets of microcapsules are loaded sequentially; or, different sets of microcapsules may also be loaded simultaneously. Similarly, multiple sets of analytes can be loaded into the device. In some cases, at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, or 20 different sets of analytes are loaded onto the device. In some cases, the different sets of analytes are loaded sequentially; or, different sets of analytes may also be loaded simultaneously.

This disclosure provides devices comprising certain numbers of microcapsules and/or analytes loaded per well. In some cases, at most 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 75, or 100 microcapsules and/or analytes are loaded into each individual microwell. In some cases, at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 75, or 100 microcapsules and/or analytes are loaded into each individual microwell. In some cases, on average, at most 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 75, or 100 microcapsules and/or analytes are loaded into each individual microwell. In other cases, on average, at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 75, or 100 microcapsules and/or analytes are loaded into each individual microwell. In some cases, about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 75, or 100 microcapsules and/or analytes are loaded into each individual microwell.

Analytes and/or microcapsules may be applied in a quantity that allows a desired number of analytes to be deposited into an individual microwell. For example, terminal dilution of analytes, such as cells, may achieve the loading of one cell per one microwell or any desired number of analytes per microwell. In some cases, a Poisson distribution is used to direct or predict the final concentration of analytes or microcapsules per well.

The microcapsules may be loaded into the microarray device in a particular pattern. For example, certain sections of the device may comprise microcapsules containing a particular reagent (e.g., unique bar-code, enzyme, antibody, antibody subclass, etc.), while other sections of the device may comprise microcapsules containing a different reagent (e.g., a different bar-code, different enzyme, different antibody different antibody subclass, etc.). In some cases, the

microcapsules in one section of the array may contain control reagents. For example, they may contain positive controls that include a control analyte and necessary materials for a reaction. Or, in some cases, the microcapsules contain negative control reagents such as deactivated enzyme, or a synthetic oligonucleotide sequence that is resistant to fragmentation. In some cases, negative control reagents may control for the specificity of the sample preparation reaction etc. In other cases, the negative control microcapsules may comprise the same reagents present in other microcapsules except that the negative control microcapsule may lack a certain reagent (e.g., lysis buffer, polymerase, etc.).

The analytes/sample also may be loaded into the microarray device in a particular pattern. For example, certain sections of the device may comprise particular analytes, such as control analytes or analytes deriving from a particular source. This may be used in combination with specific loading of bar codes into known well locations. This feature may allow mapping of specific locations on the array to sequence data, thereby reducing the number of bar codes to be used for labeling reactions.

In cases where a partition is a droplet, an analyte and reagents may be combined within the droplet with the aid of a microfluidic device. For example, a droplet may be generated that comprises a gel bead (e.g., comprising an oligonucleotide barcode) a nucleic acid analyte, and any other desired reagents. The gel bead, nucleic acid analyte, and reagents in an aqueous phase may be combined at a junction of two or more channels of a microfluidic device. At a second junction of two or more channels of the microfluidic device, a droplet comprising the resulting mixture may be generated by contacting the aqueous mixture of reagents, gel bead, and nucleic acid analyte with an oil continuous phase.

IV. Microcapsule Stimuli

Various different stimuli may be used to trigger release of reagents from the microcapsules, or from internal compartments therein. In some cases, a microcapsule is degradable. Generally, the trigger may cause disruption or degradation of the shell or membrane enveloping the microcapsule, disruption or degradation of the interior of a microcapsule, and/or disruption or degradation of any chemical bonds that immobilize a reagent to the microcapsule. Exemplary triggers include but are not limited to: chemical triggers, bulk changes, biological triggers, light triggers, thermal triggers, magnetic triggers, and any combination thereof. See, e.g., Esser-Kahn et al., (2011) *Macromolecules* 44: 5539-5553; Wang et al., (2009) *ChemPhysChem* 10:2405-2409;

A. Chemical Stimuli and Bulk Changes

Numerous chemical triggers may be used to trigger the disruption or degradation of the microcapsules. Examples of these chemical changes may include, but are not limited to pH-mediated changes to the shell wall, disintegration of the shell wall via chemical cleavage of crosslink bonds, triggered depolymerization of the shell wall, and shell wall switching reactions. Bulk changes may also be used to trigger disruption of the microcapsules.

A change in pH of the solution, particularly a decrease in pH, may trigger disruption via a number of different mechanisms. The addition of acid may cause degradation or disassembly of the shell wall through a variety of mechanisms. Addition of protons may disassemble cross-linking of polymers in the shell wall, disrupt ionic or hydrogen bonds in the shell wall, or create nanopores in the shell wall to allow the inner contents to leak through to the exterior. In some examples, the microcapsule comprises acid-degradable chemical cross-linkers such as ketals. A decrease in pH,

particular to a pH lower than 5, may induce the ketal to convert to a ketone and two alcohols and facilitate disruption of the microcapsule. In other examples, the microcapsules may comprise one or more polyelectrolytes (e.g., PAA, PAAm, PSS, etc.) that are pH sensitive. A decrease in pH may disrupt the ionic- or hydrogen-bonding interactions of such microcapsules, or create nanopores therein. In some cases, microcapsules comprising polyelectrolytes comprise a charged, gel-based core that expands and contracts upon a change of pH.

Removal of cross-linkers (e.g., disulfide bonds) within the microcapsules can also be accomplished through a number of mechanisms. In some examples, various chemicals can be added to a solution of microcapsules that induce either oxidation, reduction or other chemical changes to polymer components of the shell wall. In some cases, a reducing agent, such as beta-mercaptoethanol, dithiothreitol (DTT), or 2-tris(2-carboxyethyl)phosphine (TCEP), is added such that disulfide bonds in a microcapsule shell wall are disrupted. In addition, enzymes may be added to cleave peptide bonds within the microcapsules, thereby resulting in cleavage of shell wall cross linkers.

Depolymerization can also be used to disrupt the microcapsules. A chemical trigger may be added to facilitate the removal of a protecting head group. For example, the trigger may cause removal of a head group of a carbonate ester or carbamate within a polymer, which in turn causes depolymerization and release of reagents from the inside of the capsule.

Shell wall switching reactions may be due to any structural change to the porosity of the shell wall. The porosity of a shell wall may be modified, for example, by the addition of azo dyes or viologen derivatives. Addition of energy (e.g., electricity, light) may also be used to stimulate a change in porosity.

In yet another example, a chemical trigger may comprise an osmotic trigger, whereby a change in ion or solute concentration of microcapsule solution induces swelling of the capsule. Swelling may cause a buildup of internal pressure such that the capsule ruptures to release its contents.

It is also known in the art that bulk or physical changes to the microcapsule through various stimuli also offer many advantages in designing capsules to release reagents. Bulk or physical changes occur on a macroscopic scale, in which capsule rupture is the result of mechano-physical forces induced by a stimulus. These processes may include, but are not limited to pressure induced rupture, shell wall melting, or changes in the porosity of the shell wall.

B. Biological Stimuli

Biological stimuli may also be used to trigger disruption or degradation of microcapsules. Generally, biological triggers resemble chemical triggers, but many examples use biomolecules, or molecules commonly found in living systems such as enzymes, peptides, saccharides, fatty acids, nucleic acids and the like. For example, microcapsules may comprise polymers with peptide cross-links that are sensitive to cleavage by specific proteases. More specifically, one example may comprise a microcapsule comprising GFLGK peptide cross links. Upon addition of a biological trigger such as the protease Cathepsin B, the peptide cross links of the shell wall are cleaved and the contents of the capsule are released. In other cases, the proteases may be heat-activated. In another example, microcapsules comprise a shell wall comprising cellulose. Addition of the hydrolytic enzyme

chitosan serves as biologic trigger for cleavage of cellulosic bonds, depolymerization of the shell wall, and release of its inner contents.

C. Thermal Stimuli

The microcapsules may also be induced to release their contents upon the application of a thermal stimulus. A change in temperature can cause a variety changes to the microcapsule. A change in heat may cause melting of a microcapsule such that the shell wall disintegrates. In other cases, the heat may increase the internal pressure of the inner components of the capsule such that the capsule ruptures or explodes. In still other cases, the heat may transform the capsule into a shrunken dehydrated state. The heat may also act upon heat-sensitive polymers within the shell of a microcapsule to cause disruption of the microcapsule.

In one example, a microcapsule comprises a thermo-sensitive hydrogel shell encapsulating one or more emulsified reagent particles. Upon the application of heat, such as above 35 C, the hydrogel material of the outer shell wall shrinks. The sudden shrinkage of the shell ruptures the capsule and allows the reagents of the inside of the capsule to squirt out in the sample preparation solution in the microwell.

In some cases, the shell wall may comprise a diblock polymer, or a mixture of two polymers, with different heat sensitivities. One polymer may be particularly likely to shrink after the application of heat, while the other is more heat-stable. When heat is applied to such shell wall, the heat-sensitive polymer may shrink, while the other remains intact, causing a pore to form. In still other cases, a shell wall may comprise magnetic nanoparticles. Exposure to a magnetic field may cause the generation of heat, leading to rupture of the microcapsule.

D. Magnetic Stimuli

Inclusion of magnetic nanoparticles to the shell wall of microcapsules may allow triggered rupture of the capsules as well as guide the particles in an array. A device of this disclosure may comprise magnetic particles for either purpose. In one example, incorporation of Fe₃O₄ nanoparticles into polyelectrolyte containing capsules triggers rupture in the presence of an oscillating magnetic field stimulus.

E. Electrical and Light Stimuli

A microcapsule may also be disrupted or degraded as the result of electrical stimulation. Similar to magnetic particles described in the previous section, electrically sensitive particles can allow for both triggered rupture of the capsules as well as other functions such as alignment in an electric field, electrical conductivity or redox reactions. In one example, microcapsules containing electrically sensitive material are aligned in an electric field such that release of inner reagents can be controlled. In other examples, electrical fields may induce redox reactions within the shell wall itself that may increase porosity.

A light stimulus may also be used to disrupt the microcapsules. Numerous light triggers are possible and may include systems that use various molecules such as nanoparticles and chromophores capable of absorbing photons of specific ranges of wavelengths. For example, metal oxide coatings can be used as capsule triggers. UV irradiation of polyelectrolyte capsules coated with SiO₂/TiO₂ may result in disintegration of the capsule wall. In yet another example, photo switchable materials such as azobenzene groups may be incorporated in the shell wall. Upon the application of UV or visible light, chemicals such as these undergo a reversible cis-to-trans isomerization upon absorption of photons. In this aspect, incorporation of photo switches result in

a shell wall that may disintegrate or become more porous upon the application of a light trigger.

F. Application of Stimuli

A device of this disclosure may be used in combination with any apparatus or device that provides such trigger or stimulus. For example, if the stimulus is thermal, a device may be used in combination with a heated or thermally controlled plate, which allows heating of the microwells and may induce the rupture of capsules. Any of a number of heat transfers may be used for thermal stimuli, including but not limited to applying heat by radiative heat transfer, convective heat transfer, or conductive heat transfer. In other cases, if the stimulus is a biological enzyme, the enzyme may be injected into a device such that it is deposited into each microwell. In another aspect, if the stimulus is a magnetic or electric field, a device may be used in combination with a magnetic or electric plate.

A chemical stimulus may be added to a partition and may exert its function at various times after contacting a chemical stimulus with a microcapsule. The speed at which a chemical stimulus exerts its effect may vary depending on, for example, the amount/concentration of a chemical stimulus contacted with a microcapsule and/or the particular chemical stimulus used. For example, a droplet may comprise a degradable gel bead (e.g., a gel bead comprising chemical cross-linkers, such as, for example, disulfide bonds). Upon droplet formation, a chemical stimulus (e.g., a reducing agent) may be included in the droplet with the gel bead. The chemical stimulus may degrade the gel bead immediately on contact with the gel bead, soon after (e.g., about 0, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 min) contact with the gel bead, or at a later time. In some cases, degradation of the gel bead may occur before, during, or after a further processing step, such as, for example, a thermal cycling step as described herein.

V. Sample Preparation, Reaction and Recovery

After application of the stimulus, rupturing of capsules and release of the reagents, the sample preparation reaction may proceed in a device. Reactions within a device may be incubated for various periods of times depending on the reagents used in the sample reactions. A device may also be used in combination with other devices that aid in the sample preparation reaction. For example, if PCR amplification is desired, a device may be used in combination with a PCR thermocycler. In some cases, a thermocycler may comprise a plurality of wells. In cases where partitions are droplets, the droplets may be entered into the wells of the thermocycler. In some cases, each well may comprise multiple droplets, such that when thermal cycling is initiated, multiple droplets are thermal cycled in each well. In another example, if the reaction requires agitation, a device may be used in combination with a shaking apparatus.

Following the completion of the sample preparation reaction, the analytes and products of the sample reactions may be recovered. In some cases, a device may utilize a method comprising the application of liquid or gas to flush out the contents of the individual microwells. In one example, the liquid comprises an immiscible carrier fluid that preferentially wets the microwell array material. It may also be immiscible with water so as to flush the reaction products out of the well. In another example, the liquid may be an aqueous fluid that can be used to flush out the samples out of the wells. After flushing of the contents of the microwells, the contents of the microwells are pooled for a variety of downstream analyses and applications.

VI. Applications

FIG. 4A provides a general flow of many of the methods of the present disclosure; and FIG. 4B provides a generally annotated version of 4A. One or more microcapsule(s) that contain reagents 410 may be pre-loaded into microwells, followed by addition of an analyte, which, in this particular Figure, is a nucleic acid analyte 420. The microwells may then be sealed 430 by any method, such as by application of a sealing fluid. The inlet and outlet ports may also be sealed, for example to prevent evaporation. Following these steps, a stimulus (e.g., heat, chemical, biological, etc.) may be applied to the microwells in order to disrupt the microcapsules 460 and trigger release of the reagents 450 to the interior of the microwell. Subsequently, an incubation step 440 may occur in order to enable the reagents perform a particular function such as lysis of cells, digestion of protein, fragmentation of high molecular weight nucleic acids, or ligation of oligonucleotide bar codes. Following the incubation step (which is optional), the contents of the microwells may be recovered either singly or in bulk.

A. Analytes

A device of this disclosure may have a wide variety of uses in the manipulation, preparation, identification and/or quantification of analytes. In some cases, the analyte is a cell or population of cells. The population of cells may be homogeneous (e.g., from a cell line, of the same cell type, from the same type of tissue, from the same organ, etc.) or heterogeneous (mixture of different types of cells). The cells may be primary cells, cell lines, recombinant cells, primary cells, encapsulated cells, free cells, etc.

The analytes may also be molecules, including but not limited to: polypeptides, proteins, antibodies, enzymes, nucleic acids, saccharides, small molecules, drugs, and the like. Examples of nucleic acids include but are not limited to: DNA, RNA, dNTPs, ddNTPs, amplicons, synthetic nucleotides, synthetic polynucleotides, polynucleotides, oligonucleotides, peptide nucleic acids, cDNA, dsDNA, ssDNA, plasmid DNA, cosmid DNA, high Molecular Weight (MW) DNA, chromosomal DNA, genomic DNA, viral DNA, bacterial DNA, mtDNA (mitochondrial DNA), mRNA, rRNA, tRNA, nRNA, siRNA, snRNA, snoRNA, scaRNA, microRNA, dsRNA, ribozyme, riboswitch and viral RNA (e.g., retroviral RNA).

In some cases, the analytes are pre-mixed with one or more additional materials, such as one or more reagents (e.g., ligase, protease, polymerase) prior to being loaded into the device. In some cases, the analytes are pre-mixed with microcapsules comprising one or more reagents prior to being loaded onto the device.

The samples may be derived from a variety of sources including human, mammal, non-human mammal, ape, monkey, chimpanzee, plant, reptilian, amphibian, avian, fungal, viral or bacterial sources. Samples such as cells, nucleic acids and proteins may also be obtained from a variety of clinical sources such as biopsies, aspirates, blood draws, urine samples, formalin fixed embedded tissues and the like.

A device of this disclosure may also enable the analytes to be tagged or tracked in order to permit subsequent identification of an origin of the analytes. This feature is in contrast with other methods that use pooled or multiplex reactions and that only provide measurements or analyses as an average of multiple samples. Here, the physical partitioning and assignment of a unique identifier to individual analytes allows acquisition of data from individual samples and is not limited to averages of samples.

In some examples, nucleic acids or other molecules derived from a single cell may share a common tag or

identifier and therefore may be later identified as being derived from that cell. Similarly, all of the fragments from a single strand of nucleic acid may be tagged with the same identifier or tag, thereby permitting subsequent identification of fragments with similar phasing or linkage on the same strand. In other cases, gene expression products (e.g., mRNA, protein) from an individual cell may be tagged in order to quantify expression. In still other cases, the device can be used as a PCR amplification control. In such cases, multiple amplification products from a PCR reaction can be tagged with the same tag or identifier. If the products are later sequenced and demonstrate sequence differences, differences among products with the same identifier can then be attributed to PCR error.

The analytes may be loaded onto the device before, after, or during loading of the microcapsules and/or free reagents. In some cases, the analytes are encapsulated into microcapsules before loading into the microcapsule array. For example, nucleic acid analytes may be encapsulated into a microcapsule, which is then loaded onto the device and later triggered to release the analytes into an appropriate microwell.

Any analytes, such as DNA or cells, may be loaded in solution or as analytes encapsulated in a capsule. In some cases, homogeneous or heterogeneous populations of molecules (e.g., nucleic acids, proteins, etc.) are encapsulated into microcapsules and loaded onto the device. In some cases, homogeneous or heterogeneous populations of cells are encapsulated into microcapsules and loaded onto the device. The microcapsules may comprise a random or specified number of cells and/or molecules. For example, the microcapsules may comprise no more than 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 500, 1000, 5000, or 10000 cells and/or molecules per microcapsule. In other examples, the microcapsules comprise at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 500, 1000, 5000, or 10000 cells and/or molecules per microcapsule. Fluidic techniques and any other techniques may be used to encapsulate the cells and/or molecules into the microcapsules.

Generally, the methods and compositions provided herein are useful for preparation of an analyte prior to a downstream application such as a sequencing reaction. Often, a sequencing method is classic Sanger sequencing. Sequencing methods may include, but are not limited to: high-throughput sequencing, pyrosequencing, sequencing-by-synthesis, single-molecule sequencing, nanopore sequencing, sequencing-by-ligation, sequencing-by-hybridization, RNA-Seq (Illumina), Digital Gene Expression (Helicos), Next generation sequencing, Single Molecule Sequencing by Synthesis (SMSS)(Helicos), massively-parallel sequencing, Clonal Single Molecule Array (Solexa), shotgun sequencing, Maxim-Gilbert sequencing, primer walking, and any other sequencing methods known in the art.

There are numerous examples of applications that may be conducted instead of, or in conjunction with, a sequencing reaction, including but not limited to: biochemical analyses, proteomics, immunoassays, profiling/fingerprinting of specific cell types, pharmaceutical screening, bait-capture experiments, protein-protein interaction screens and the like.

B. Assignment of Unique Identifiers to Analytes

The devices disclosed herein may be used in applications that involve the assignment of unique identifiers, or molecular bar codes, to analytes. Often, the unique identifier is a bar-code oligonucleotide that is used to tag the analytes; but, in some cases, different unique identifiers are used. For

example, in some cases, the unique identifier is an antibody, in which case the attachment may comprise a binding reaction between the antibody and the analyte (e.g., antibody and cell, antibody and protein, antibody and nucleic acid). In other cases, the unique identifier is a dye, in which case the attachment may comprise intercalation of the dye into the analyte molecule (such as intercalation into DNA or RNA) or binding to a probe labeled with the dye. In still other cases, the unique identifier may be a nucleic acid probe, in which case the attachment to the analyte may comprise a hybridization reaction between the nucleic acid and the analyte. In some cases, the reaction may comprise a chemical linkage between the identifier and the analyte. In other cases, the reaction may comprise addition of a metal isotope, either directly to the analyte or by a probe labeled with the isotope.

Often, the method comprises attaching oligonucleotide bar codes to nucleic acid analytes through an enzymatic reaction such as a ligation reaction. For example, the ligase enzyme may covalently attach a DNA bar code to fragmented DNA (e.g., high molecular-weight DNA). Following the attachment of the bar-codes, the molecules may be subjected to a sequencing reaction.

However, other reactions may be used as well. For example, oligonucleotide primers containing bar code sequences may be used in amplification reactions (e.g., PCR, qPCR, reverse-transcriptase PCR, digital PCR, etc.) of the DNA template analytes, thereby producing tagged analytes. After assignment of bar codes to individual analytes, the contents of individual microwells may be recovered via the outlet port in the device for further analyses.

The unique identifiers (e.g., oligonucleotide bar-codes, antibodies, probes, etc.) may be introduced to the device randomly or nonrandomly. In some cases, they are introduced at an expected ratio of unique identifiers to microwells. For example, the unique identifiers may be loaded so that more than about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 100, 500, 1000, 5000, 10000, or 200000 unique identifiers are loaded per microwell. In some cases, the unique identifiers may be loaded so that less than about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 100, 500, 1000, 5000, 10000, or 200000 unique identifiers are loaded per microwell. In some cases, the average number of unique identifiers loaded per microwell is less than, or greater than, about 0.0001, 0.001, 0.01, 0.1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 100, 500, 1000, 5000, 10000, or 200000 unique identifiers per microwell.

The unique identifiers also may be loaded so that a set of one or more identical identifiers are introduced to a particular well. Such sets may also be loaded so that each microwell contains a different set of identifiers. For example, a population of microcapsules may be prepared such that a first microcapsule in the population comprises multiple copies of identical unique identifiers (e.g., nucleic acid bar codes, etc.) and a second microcapsule in the population comprises multiple copies of a unique identifier that differs from within the first microcapsule. In some cases, the population of microcapsules may comprise multiple microcapsules (e.g., greater than 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 100, 500, 1000, 5000, 10000, 100000, 1000000, 10000000, or 1000000000 microcapsules), each containing multiple copies of a unique identifier that differs from that contained in the other microcapsules. In some cases, the population may comprise greater than 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 100, 500, 1000, 5000, 10000, 100000, 1000000, 10000000, or 1000000000 microcapsules with identical sets of unique identifiers. In some cases, the population may comprise

greater than 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 100, 500, 1000, 5000, 10000, 100000, 1000000, 10000000, or 1000000000 microcapsules, wherein the microcapsules each comprise a different combination of unique identifiers. For example, in some cases the different combinations overlap, such that a first microcapsule may comprise, e.g., unique identifiers A, B, and C, while a second microcapsule may comprise unique identifiers A, B, and D. In another example, the different combinations do not overlap, such that a first microcapsule may comprise, e.g., unique identifiers A, B, and C, while a second microcapsule may comprise unique identifiers D, E, and F.

The unique identifiers may be loaded into the device at an expected or predicted ratio of unique identifiers per analyte (e.g., strand of nucleic acid, fragment of nucleic acid, protein, cell, etc.) In some cases, the unique identifiers are loaded in the microwells so that more than about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 100, 500, 1000, 5000, 10000, or 200000 unique identifiers are loaded per individual analyte in the microwell. In some cases, the unique identifiers are loaded in the microwells so that less than about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 100, 500, 1000, 5000, 10000, or 200000 unique identifiers are loaded per individual analyte in the microwell. In some cases, the average number of unique identifiers loaded per analyte is less than, or greater than, about 0.0001, 0.001, 0.01, 0.1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 100, 500, 1000, 5000, 10000, or 200000 unique identifiers per analyte. When more than one identifier is present per analyte, such identifiers may be copies of the same identifier, or multiple different identifiers. For example, the attachment process may be designed to attach multiple identical identifiers to a single analyte, or multiple different identifiers to the analyte.

The unique identifiers may be used to tag a wide range of analytes, including cells or molecules. For example, unique identifiers (e.g., bar code oligonucleotides) may be attached to whole strands of nucleic acids or to fragments of nucleic acids (e.g., fragmented genomic DNA, fragmented RNA). The unique identifiers (e.g., antibodies, oligonucleotides) may also bind to cells, include the external surface of a cell, a marker expressed on the cell or components within the cell such as organelles, gene expression products, genomic DNA, mitochondrial DNA, RNA, mRNA, or proteins. The unique identifiers also may be designed to bind or hybridize nucleic acids (e.g., DNA, RNA) present in permeabilized cells, which may or may not be otherwise intact.

The unique identifiers may be loaded onto the device either singly or in combination with other elements (e.g., reagents, analytes). In some cases, free unique identifiers are pooled with the analytes and the mixture is loaded into the device. In some cases, unique identifiers encapsulated in microcapsules are pooled with the analytes, prior to loading of the mixture onto the device. In still other cases, free unique identifiers are loaded into the microwells prior to, during (e.g., by separate inlet port), or following the loading of the analytes. In still other cases, unique identifiers encapsulated in microcapsules are loaded into the microwells prior to, concurrently with (e.g., by separate inlet port), or after loading of the analytes.

In many applications, it may be important to determine whether individual analytes each receive a different unique identifier (e.g., oligonucleotide bar code). If the population of unique identifiers introduced into the device is not significantly diverse, different analytes may possibly be tagged with identical identifiers. The devices disclosed herein may enable detection of analytes tagged with the same identifier. In some cases, a reference analyte may be included with the

population of analytes introduced into the device. The reference analyte may be, for example, a nucleic acid with a known sequence and a known quantity. After the population of analytes is loaded and partitioned in the device, unique identifiers may be attached to the analytes, as described herein. If the unique identifiers are oligonucleotide bar codes and the analytes are nucleic acids, the tagged analytes may subsequently be sequenced and quantified. These methods may indicate if one or more fragments and/or analytes may have been assigned an identical bar code.

A method disclosed herein may comprise loading the device with the reagents necessary for the assignment of bar codes to the analytes. In the case of ligation reactions, reagents including, but not limited to, ligase enzyme, buffer, adapter oligonucleotides, a plurality of unique identifier DNA bar codes and the like may be loaded into the device. In the case of enrichment, reagents including but not limited to a plurality of PCR primers, oligonucleotides containing unique identifying sequence, or bar code sequence, DNA polymerase, DNTPs, and buffer and the like may be loaded into the device. The reagents may be loaded as free reagents or as reagents encapsulated in microcapsules.

C. Nucleic Acid Sequencing

Nucleic acid sequencing may begin with the physical partitioning of sample analytes into microwells at a particular density (e.g., about 1 analyte per microwell or other density described herein). When nucleic acid bar codes are assigned to individual analytes, it may then be possible to track individual molecules during subsequent steps such as subsequent amplification and/or sequencing steps, even if the analytes are later pooled together and treated en masse.

a. Nucleic Acid Phasing

The devices provided herein may be used to prepare analytes (e.g., nucleic acid analytes) in such a manner that enables phasing or linkage information to be subsequently obtained. Such information may allow for the detection of linked genetic variations in sequences, including genetic variations (e.g., SNPs, mutations, indels, copy number variations, transversions, translocations, inversions, etc.) that are separated by long stretches of nucleic acids. These variations may exist in either a cis or trans relationship. In cis relationships, two or more genetic variations may exist in the same polynucleic acid molecule or strand. In trans relationships, two or more genetic variations may exist on multiple nucleic acid molecules or strands.

A method of determining nucleic acid phasing may comprise loading a nucleic acid sample (e.g., a nucleic acid sample that spans a given locus or loci) into a device disclosed herein, distributing the sample such that at most one molecule of nucleic acid is present per microwell, and fragmenting the sample within the microwells. The method may further comprise attaching unique identifiers (e.g., bar codes) to the fragmented nucleic acids as described herein, recovering the nucleic acids in bulk, and performing a subsequent sequencing reaction on the samples in order to detect genetic variations, such as two different genetic variations. The detection of genetic variations tagged with two different bar codes may indicate that the two genetic variations are derived from two separate strands of DNA, reflecting a trans relationship. Conversely, the detection of two different genetic variations tagged with the same bar codes may indicate that the two genetic variations are from the same strand of DNA, reflecting a cis relationship.

Phase information may be important for the characterization of the analyte, particularly if the analyte derives from a subject at risk of, having, or suspected of a having a particular disease or disorder (e.g., hereditary recessive

disease such as Cystic Fibrosis, cancer, etc.). The information may be able to distinguish between the following possibilities: (1) two genetic variations within the same gene on the same strand of DNA and (2) two genetic variations within the same gene but located on separate strands of DNA. Possibility (1) may indicate that one copy of the gene is normal and the individual is free of the disease, while possibility (2) may indicate that the individual has or will develop the disease, particularly if the two genetic variations are damaging to the function of the gene when present within the same gene copy. Similarly, the phasing information may also be able to distinguish between the following possibilities: (1) two genetic variations, each within a different gene on the same strand of DNA and (2) two genetic variations, each within a different gene but located on separate strands of DNA.

b. Cell-Specific Information

The devices provided herein may be used to prepare cellular analytes in such a manner that enables cell-specific information to be subsequently obtained. Such information may enable detection of genetic variations (e.g., SNPs, mutations, indels, copy number variations, transversions, translocations, inversions, etc.) on a cell-by-cell basis, thereby enabling a determination of whether the genetic variation(s) are present in the same cell or two different cells.

A method of determining nucleic acid cell-specific information may comprise loading a cellular sample (e.g., a cellular sample from a subject) into a device disclosed herein, distributing the sample such that at most one cell is present per microwell, lysing the cells, and then tagging the nucleic acids within the cells with unique identifiers using a method described herein. In some cases, microcapsules comprising unique identifiers are loaded in the microwell array device (either before, during, or after the loading of the cellular analytes) in such a manner that each cell is contacted with a different microcapsule. The resulting tagged nucleic acids can then be pooled, sequenced, and used to trace the origin of the nucleic acids. Nucleic acids with identical unique identifiers may be determined to originate from the same cell, while nucleic acids with different unique identifiers may be determined to originate from different cells.

In a more specific example, the methods herein may be used to detect the distribution of oncogenic mutations across a population of cancer tumor cells. In this example, some of the cells may have a mutation, or amplification, of an oncogene (e.g., HER2, BRAF, EGFR, KRAS) on two strands of DNA (homozygous), while others may be heterozygous for the mutation, while still other cells may be wild-type and comprise no mutations or other variation in the oncogene. The methods described herein may be able to detect these differences, and also may enable quantification of the relative numbers of homozygous, heterozygous, and wild-type cells. Such information may be used to stage a particular cancer or to monitor the progression of the cancer over time.

In some examples, this disclosure provides methods of identifying mutations in two different oncogenes (e.g., KRAS and EGFR). If the same cell comprises genes with both mutations, this may indicate a more aggressive form of cancer. In contrast, if the mutations are located in two different cells, this may indicate that the cancer is more benign, or less advanced.

The following is another specific example of cell-specific sequence determination. In this example, a plurality of cells, such as from a tumor biopsy, is loaded into a device. Single cells from the sample are deposited into individual wells and labeled with a DNA bar code.

Loading of cells into a device may be achieved through non-random loading. Parameters for non-random loading of analytes, such as cells, may be understood using an interference function such that:

$$\text{“fraction multi-occupancy”} = 1 - \left[\left(1 - \frac{1}{N} \right) + \frac{P}{N} \right]^C$$

where

P=probability that a particular cell will attempt but not fit in the well (measure of interference)

N=number of wells

L=number of labels=barcodes

C=number of cells

As part of sample preparation reactions, cells may be lysed and many subsequent reactions are possible, including RNA amplification, DNA amplification or antibody screening for different target proteins and genes in individual cells. After the reaction, the contents of the cells may be pooled together and could be further analyzed, such as by DNA sequencing. With each cell assigned a unique barcode, further analyses may be possible including but not limited to quantification of different gene levels or nucleic acid sequencing of individual cells. In this example, it may be determined whether the tumor comprises cells with different genetic backgrounds (e.g., cancer clones and subclones). The relative number of each type of cell may also be calculated.

c. Amplification Control

As disclosed herein, the device can be used for purposes of controlling for amplification errors, such as PCR errors. For example, a nucleic acid sample may be partitioned into the microwells of the device. Following partitioning, the sample may be subjected to a PCR amplification reaction within the microwells. The PCR products within a microwell may be tagged with the same unique identifier, using a method described herein. If the products are later sequenced and demonstrate sequence differences, differences among products with the same identifier can then be attributed to PCR error.

d. Gene-expression Products Analysis

In other applications, a device may be used to detect gene product (e.g., protein, mRNA) expression levels in a sample, often on a cell-by-cell basis. A sample may comprise individual cells, a pool of mRNA extract from cells, or other collection of gene products. In some instances, single cells may be loaded into microwells. In other instances, a pool of mRNA or other gene product may be loaded such that a desired quantity of mRNA molecules is loaded into individual microwells.

The methods provided herein may be particularly useful for RNA analysis. For example, using the methods provided herein, unique identifiers may be assigned to mRNA analytes either directly or to cDNA products of a reverse transcription reaction performed on the mRNA analytes. The reverse transcription reaction may be conducted within the microwells of the device following loading of the analytes. Reagents for the reaction may include but are not limited to reverse transcriptase, DNA polymerase enzyme, buffer, dNTPs, oligonucleotide primers, oligonucleotide primers containing bar code sequences and the like. One or more reagents may be loaded into microcapsules or loaded freely in solution into the device or a combination thereof. Sample preparation may then be conducted, such as by fragmenting the cDNA and attaching unique identifiers to the fragments.

After sample preparation and recovery, the nucleic acid products of the reaction may be further analyzed, such as by sequencing.

Additionally, a device may be used to characterize multiple cell markers, similar to a flow cytometer. Any cell marker may be characterized, including cell-surface markers (e.g., extracellular proteins, transmembrane markers) and markers located within the internal portion of a cell (e.g., RNA, mRNA, microRNA, multiple copies of genes, proteins, alternative splicing products, etc.). For example, cells may be partitioned within the device, as described herein, so that at most one cell is present within a microwell. Cell markers such as nucleic acids (e.g., RNA) may be extracted and/or fragmented prior to being labeled with a unique identifier (e.g., molecular bar code). Or, alternatively, the nucleic acids may be labeled with a unique identifier without being extracted and/or fragmented. The nucleic acids may then be subjected to further analysis such as sequencing reactions designed to detect multiple gene expression products. Such analysis may be useful in a number of fields. For example, if the starting cells are immune cells (e.g., T cells, B cells, macrophages, etc.), the analysis may provide information regarding multiple expressed markers and enable immunophenotyping of the cells, for example by identifying different CD markers of the cells (e.g., CD3, CD4, CD8, CD19, CD20, CD 56, etc.). Such markers can provide insights into the function, character, class, or relative maturity of the cell. Such markers can also be used in conjunction with markers that are not necessarily immunophenotyping markers, such as markers of pathogenic infection (e.g., viral or bacterial protein, DNA, or RNA). In some cases, the device may be used to identify at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 200, 500, 700, 1000, 5000, 10000, 50000, or 100000 different gene expression products or other form of cellular markers on a single-cell basis. Often, such methods do not comprise use of dyes or probes (e.g., fluorescent probes or dyes).

Gene expression product analysis may be useful in numerous fields including immunology, cancer biology (e.g., to characterize the existence, type, stage, aggressiveness, or other characteristic of cancerous tissue), stem cell biology (e.g., in order to characterize the differentiation state of a stem cell, potency of a stem cell, cellular type of a stem cell, or other features of a stem cell), microbiology, and others. The gene expression analysis may also be used in drug screening applications, for example to evaluate the effect of a particular drug or agent on the gene expression profile of particular cells.

VII. Terminology

The terminology used therein is for the purpose of describing particular embodiments only and is not intended to be limiting of a device of this disclosure. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. Furthermore, to the extent that the terms “including”, “includes”, “having”, “has”, “with”, or variants thereof are used in either the detailed description and/or the claims, such terms are intended to be inclusive in a manner similar to the term “comprising”.

Several aspects of a device of this disclosure are described above with reference to example applications for illustration. It should be understood that numerous specific details, relationships, and methods are set forth to provide a full understanding of a device. One having ordinary skill in the relevant art, however, will readily recognize that a device

can be practiced without one or more of the specific details or with other methods. This disclosure is not limited by the illustrated ordering of acts or events, as some acts may occur in different orders and/or concurrently with other acts or events. Furthermore, not all illustrated acts or events are required to implement a methodology in accordance with this disclosure.

Ranges can be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another embodiment. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint. The term “about” as used herein refers to a range that is 15% plus or minus from a stated numerical value within the context of the particular usage. For example, about 10 would include a range from 8.5 to 11.5.

The term microwell array, as used herein, generally refers to a predetermined spatial arrangement of microwells. Microwell array devices that comprise a microcapsule may also be referred to as “microwell capsule arrays.” Further, the term “array” may be used herein to refer to multiple arrays arranged on a surface, such as would be the case where a surface has multiple copies of an array. Such surfaces bearing multiple arrays may also be referred to as “multiple arrays” or “repeating arrays.”

EXAMPLE 1

Single Cell DNA Sequencing

A microwell capsule array is prepared to perform nucleic acid sequencing on individual human B-cells taken from a blood sample. Approximately 15,000 cells are harvested and used for loading into the device. A device of this disclosure and containing 150,000 microwells is used. Each well is cylindrical in shape having a diameter of 125 μm and a height of 125 μm , allowing at most 1 capsule to be loaded per well. Microcapsules made through emulsion polymerization with a PNIPAM hydrogel shell wall are created such that the microcapsules have a diameter of 100 μm for loading in the device. The microcapsules are created such that the PNIPAM shell contains magnetic iron particles. The outer surface of the shell is then chemically coupled to an antibody specific to a transmembrane B cell receptor on the outside of a B cell.

During the preparation process of capsules, reagents are simultaneously loaded into the capsules. Reagents necessary for cell lysis and labeling individual DNA strands of the cells with DNA barcodes are loaded into capsules. Reagents for cell lysis include a mild non-ionic detergent, buffer and salt. Reagents for the addition of DNA bar codes to genomic DNA included restriction enzymes, ligase, and >10,000,000 unique DNA oligonucleotides are loaded into capsules. Capsules are designed to be sensitive to rupture at greater than 65 C.

Capsules are prepared to be applied to the microcapsule array. The array is placed on a magnetic temperature controlled hot plate. Microcapsules are added to a sample of B cells such that one B cell is able to bind to one capsule. Capsule-cell conjugates are applied in aqueous carrier solution in a quantity in excess to the relative number of wells. Gentle pipetting of capsules-cells into the inlet port followed

by application of a vacuum manifold to the outlet port distributes the capsules throughout the device. A magnetic field is applied through the plate. Excess capsule-cell solution is removed via pipetting through the outlet port. Each capsule-cell conjugate is trapped and positioned in individual wells via the magnetic field.

After the cells and capsules are loaded in the device, a carrier oil (or sealing fluid) is applied to the device to remove any excess aqueous solution bridging adjacent microwells. The carrier oil applied to the inlet and excess oil is recovered at the outlet with a vacuum manifold. After the carrier oil is applied, the inlet and outlet ports are sealed with tape.

The device is then heated, via the magnetic temperature controlled hot plate, to a temperature of 70 C for 10 min to allow for capsule rupture and cell lysis. The hot plate is then switched to 37 C, for restriction and ligation, for up to 1 hour.

After the sample preparation reaction is completed, the contents of the wells are recovered. The inlet and outlet ports of the device are unsealed and nitrogen gas is applied to the device to flush out the individual components of the microwells. The sample is collected in bulk via a pipette at the outlet port, while the magnetic field retains ruptured capsule shells in individual microwells.

The sample is then sequenced using a multiplex sequencing strategy known in the art. Bar coding of individual cells allows for sequencing information to be gained for individual cells rather than as an average of multiple cells. Based upon the number of cells sequenced and bar codes assigned, SNP cell-specific information is gained. Moreover, the number of reads for individual bar codes can be counted to provide insight into the distribution of different types of cells with varying genetic backgrounds, within the original population of B cells.

EXAMPLE 2

DNA Single Strand Sequencing

A microwell capsule array is prepared to perform nucleic acid sequencing on individual strands of DNA isolated from a population of human skin cells. Cells are lysed using detergent and heat and approximately 15,000 copies of diploid DNA are precipitated via chloroform/ethanol extraction. A resuspension of DNA is loaded into the device with approximately 10,000 copies of haploid DNA. A device of this disclosure, with 300,000 microwells is used. Each well is cylindrical in shape having a diameter of 125 μm and a height of 125 μm , allowing at most 1 capsule to be loaded per well. Microcapsules made through emulsion polymerization with a PNIPAM hydrogel shell wall are created to a specification of a sphere with a diameter of 100 μm for loading into the device.

During the preparation of the microcapsules, reagents are simultaneously loaded into the capsules. The reagents include reagents necessary for labeling individual DNA strands with DNA barcodes, including restriction enzymes, ligase, and >10,000,000 unique DNA oligonucleotides. Capsules designed to be sensitive to rupture at greater than 65 C are used for the encapsulation.

Capsules are applied aqueous carrier solution in an excess to the relative number of wells. Gentle pipetting of capsules into the inlet followed by application of a vacuum manifold to the outlet distributed the capsules throughout the device.

After excess capsule solution is removed, a suspension of DNA in buffer is applied to the device in a similar fashion as the capsules.

After the DNA strands and capsules are loaded in the device, a carrier oil is applied to the device to remove any excess aqueous solution bridging adjacent microwells. The carrier oil is applied to the inlet port and excess oil is recovered at the outlet port with a vacuum manifold. After the carrier oil is applied, the inlet and outlet ports are sealed with tape.

The device is then placed on a temperature controlled hot plate and heated to temperature of 70 C for 10 min to allow for capsule rupture. Reagents are released into the sample preparation reaction. The hot plate is then switched to 37 C, for restriction and ligation, for up to 1 hour.

After the sample preparation reaction is completed, the inlet and outlet ports of the device are unsealed and nitrogen gas is applied to the device to flush out the individual components of the microwells. The sample products, en bulk, are collected via pipette at the outlet port.

The sample is then sequenced to sufficient coverage (e.g., 500) using a multiplex sequencing strategy known in the art. Bar coding of individual DNA strands allows for sequencing information to be gained from individual strands rather than as an average of entire sample of DNA. Based upon the number of DNA strands sequenced and bar codes assigned, SNP phasing/haplotyping information is gained and many repetitive regions of DNA can be resolved. In addition, a substantial boost in accuracy can be gained by discarding mutations that appear randomly with respect to haplotypes, as those are likely to be sequencing errors.

It should be understood from the foregoing that, while particular implementations have been illustrated and described, various modifications may be made thereto and are contemplated herein. It is also not intended that the invention be limited by the specific examples provided within the specification. While the invention has been described with reference to the aforementioned specification, the descriptions and illustrations of the preferable embodiments herein are not meant to be construed in a limiting sense. Furthermore, it shall be understood that all aspects of the invention are not limited to the specific depictions, configurations or relative proportions set forth herein which depend upon a variety of conditions and variables. Various modifications in form and detail of the embodiments of the invention will be apparent to a person skilled in the art. It is therefore contemplated that the invention shall also cover any such modifications, variations and equivalents. It is intended that the following claims define the scope of the invention and that methods and structures within the scope of these claims and their equivalents be covered thereby.

What is claimed is:

1. A method for droplet generation, comprising:

- (a) providing at least 1,000,000 oligonucleotide molecules comprising barcode sequences, wherein said barcode sequences are the same sequence for said at least 1,000,000 oligonucleotide molecules, wherein said at least 1,000,000 oligonucleotide molecules are releasably attached to a bead, wherein said bead is porous;
- (b) combining said at least 1,000,000 oligonucleotide molecules and a sample comprising a nucleic acid analyte each in an aqueous phase at a first junction of two or more channels of a microfluidic device to form

an aqueous mixture comprising said at least 1,000,000 oligonucleotide molecules attached to said bead and said sample; and

- (c) generating a droplet comprising said at least 1,000,000 oligonucleotide molecules attached to said bead and said sample comprising said nucleic acid analyte by contacting said aqueous mixture with an immiscible continuous phase at a second junction of two or more channels of said microfluidic device.

2. The method of claim 1, further comprising, in (b), combining said at least 1,000,000 oligonucleotide molecules attached to said bead, said nucleic acid analyte and one or more reagents necessary for amplification of said nucleic acid analyte at said first junction to form said aqueous mixture comprising said at least 1,000,000 oligonucleotide molecules attached to said bead, said nucleic acid analyte and said one or more reagents.

3. The method of claim 2, wherein in (c), said droplet further comprises said one or more reagents.

4. The method of claim 3, wherein said one or more reagents comprises a polymerase.

5. The method of claim 4, wherein said polymerase is unable to recognize uracil.

6. The method of claim 1, wherein said bead comprises a polyacrylamide.

7. The method of claim 1, wherein said bead is a gel bead.

8. The method of claim 1, wherein said at least 1,000,000 oligonucleotide molecules comprise uracil.

9. The method of claim 1, wherein a given oligonucleotide molecule of said at least 1,000,000 oligonucleotide molecules comprises a region which functions as a primer.

10. The method of claim 9, wherein said region which functions as said primer has a sequence for random priming.

11. The method of claim 9, further comprising, after (c), amplifying said nucleic acid analyte with said primer.

12. The method of claim 1, wherein said nucleic acid analyte is selected from the group consisting of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), amplicons, synthetic polynucleotides, polynucleotides, oligonucleotides, cDNA, dsDNA, ssDNA, plasmid DNA, cosmid DNA, High Molecular Weight (MW) DNA, chromosomal DNA, genomic DNA, viral DNA, bacterial DNA, mtDNA (mitochondrial DNA), mRNA, rRNA, tRNA, nRNA, siRNA, snRNA, snoRNA, scaRNA, microRNA, dsRNA, ribozyme, riboswitch and viral RNA.

13. The method of claim 1, wherein said at least 1,000,000 oligonucleotide molecules are attached to said bead via a chemical cross-linker.

14. The method of claim 1, wherein said at least 1,000,000 oligonucleotide molecules are attached to said bead via a disulfide bond.

15. The method of claim 1, wherein said at least 1,000,000 oligonucleotide molecules are attached to said bead via a covalent bond.

16. The method of claim 1, wherein said at least 1,000,000 oligonucleotide molecules are attached to said bead via a labile moiety.

17. The method of claim 1, wherein said bead is degradable upon application of a stimulus.

18. The method of claim 17, further comprising applying said stimulus to the droplet to release said at least 1,000,000 oligonucleotide molecules from said bead into said droplet.

19. The method of claim 18, wherein said stimulus is selected from the group consisting of a biological stimulus, a chemical stimulus, a thermal stimulus, an electrical stimulus, a magnetic stimulus, and a photo stimulus.

20. The method of claim 19, wherein said stimulus is a chemical stimulus that is a reducing agent.

21. The method of claim 1, wherein subsequent to generating said droplet in (c), a given oligonucleotide molecule of said at least 1,000,000 oligonucleotide molecules attaches 5 to said nucleic acid analyte, and wherein said given oligonucleotide molecule attached to said given nucleic acid analyte is subjected to nucleic acid amplification to yield a barcoded nucleic acid analyte.

22. The method of claim 1, wherein said bead comprises 10 a chemical cross-linker.

23. The method of claim 22, wherein said chemical cross-linker is a disulfide bond.

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