ARTIFICIAL DIELECTRICS USING NANOSTRUCTURES

Background of the Invention

Field of the Invention

[0001] The invention relates to nanowires, and more particularly to controllable artificial dielectrics using nanowires.

Background Art

[0002] Dielectrics are materials that are used primarily to isolate components electrically from each other or to act as capacitive elements in devices, circuits and systems. A unique characteristic of a dielectric is that nearly all or a portion of the energy required for its charging from an external electrical field can be recovered when the field is removed. Dielectrics have an extremely wide range of applications, including but not limited to, electrical components used in communications to radar absorbing materials (RAM).

[0003] Example dielectric materials include polyethylene, polypropylene, polystyrene, cross-linked polystyrene, fused silica, fused quartz, Alumina (Al_2O_3), Boron Nitride (BN), Beryllium Oxide (BeO) and Magnesium Oxide (MgO). Polyethylene is one of the most common solid dielectrics, which is extensively used as a solid dielectric extruded insulant in power and communication cables. Polypropylene also has many electrical applications both in bulk form and in molded and extruded insulations as well as in film form in taped capacitor, transformer and cable insulations. Alumina is used for dielectric substrates in microcircuit applications. Magnesium oxide is a common inorganic insulating material which is utilized for insulating heating elements in ovens. A wide range of dielectric materials exist with a wide range of applications. Further discussion of dielectric materials and their uses can be found in R. Bartnikas, *Dielectrics and Insulators*, in The Electrical Engineering Handbook 1143-1150 (Michael C. Dorf, ed. CRC Press 1993), which is herein incorporated in its entirety by reference.

[0004] Two fundamental parameters characterize a dielectric material. These are conductivity, σ, and the value of the real permittivity or dielectric constant, ε_r. The conductivity is equal to the ratio of the dielectric's leakage current density J_l to an applied electric field E. Equation (1) provides this relationship:

$$\sigma = J_l/E \qquad (1)$$

[0005] The dielectric constant, ε_r, is determined from the ratio:

$$\varepsilon_r = C/C_o \qquad (2)$$

where, C represents the measured capacitance in fahrad (F) and C_o is the equivalent capacitance in vacuum, which is calculated for the same specimen geometry from $C_o = \varepsilon_o A/d$. ε_o denotes the permittivity of the dielectric in vacuum and is equal to 8.854×10^{-14} Fcm^{-1}. A is the surface area of the dielectric and d is the thickness of the dielectric. Liquid and solid dielectric materials typically have dielectric constants ranging from approximately 2 to 10. Example approximate dielectric constants for common dielectrics at 20°C with a 1 Mhz signal are as follows.

Dielectric	**Dielectric Constant**
Alumina	8.5
Magnesium Oxide	9.69
Polypropylene	2.3
Polyethylene	2.25

[0006] An important dielectric characteristic is the dielectric loss or dissipation factor. Under alternating current (AC) conditions dielectric loss arises mainly from the movement of free charge carriers (electrons and ions), space charge polarization, and dipole orientation. Ionic, space charge, and

dipole losses are temperature and frequency dependent, a dependency which is reflected in the measured valued of σ and ε_r. This necessitates the introduction of a complex permittivity defined by

$$\varepsilon = \varepsilon_r - j\,\varepsilon_i \qquad (3)$$

where ε_i is the imaginary value of the permittivity.

[0007] The complex permittivity, ε_i, is equal to the ratio of the dielectric displacement vector D to the electric field vector E, as given by

$$\varepsilon_i = D/E \qquad (4)$$

[0008] Under AC conditions the appearance of a loss or leakage current is manifest as a phase angle difference between the D and E vectors. D and E may be expressed as:

$$D = D_o \exp[j(\omega t - \delta)] \qquad (5)$$

$$E = E_o \exp[j\omega t] \qquad (6)$$

Where ω is the radial frequency term, t the time, δ is a phase difference between D and E, and D_0 and E_0 the respective magnitudes of the two vectors. From these relationships it follows that

$$\varepsilon_r = D_o/E_o * \cos\delta \qquad (7)$$

$$\varepsilon_i = D_0/E_0 * \sin\delta \qquad (8)$$

[0009] Under AC conditions the magnitude of loss of a given material is defined as its dissipation factor, $\tan\delta$. From equations (7) and (8), the dissipation factor can be represented as

$$\tan\delta = \varepsilon_i / \varepsilon_r = \sigma/\omega\,\varepsilon_r \qquad (9)$$

[0010] These basic characteristics and example dielectric materials illustrate the wide range of dielectrics, applications and characteristics. Nonetheless,

the desire to employ dielectrics with more robust operating characteristics for evermore increasing applications combined with the physical limitations of dielectric materials, led to the development of a wide variety of dielectric structures and the creation of artificial dielectrics.

[0011] An example of a dielectric structure developed for shielding electromagnetic energy is provided in United States Patent No. 5,583,318, entitled *Multi-Layer Shield for Absorption of Electromagnetic Energy*, issued to Powell on Dec. 10, 1996 ('318 Patent). The '318 Patent teaches a multi-layer structure for shielding electromagnetic energy in a data processing equipment enclosure. The multi-layer structure is designed to substantially reduce spurious transmissions from a source within the data processing equipment enclosure by absorbing the electromagnetic energy and dissipating the electromagnetic energy as heat within the multi-layer structure. The multi-layer structure is formed by stacking various layers of dielectric, conductive and/or polymer materials together. The effective impedance of the multi-layer structure is changed by selecting different combinations of materials to change the effective properties of the shielding structure.

[0012] Another example of a dielectric structure and process for producing such a structure is given in United States patent number 6,589,629, entitled *Process for Fabricating Patterned, Functionalized Particles and Article Formed from Particles*, issued to Bao et al., on July 8, 2003 ('629 Patent). The '629 Patent teaches a technique for forming functionalized particles, where such particles are readily formed into periodic structures. The functionalized particles are capable of being formed into an ordered structure, by selection of appropriate complementary functionalizing agents on a substrate and/or on other particles. This process can be used to develop photonic band gap (PBG) materials. PBG materials are potentially useful as waveguides and microcavities for lasers, filters, polarizers, and planar antenna substrates. A PBG material is generally formed by combining a high refractive index dielectric material with a three dimensional lattice of another material having a low refractive index, to form a three-dimensional Bragg

grating. The propagation of light in the PBG structure therefore depends on the particular energy of the photon.

[0013] Investigations have been made into the formation of artificial dielectric composites by the inclusion of high-aspect ratio conductive filaments into polymer matrices. W. Stockton, et al., *Artificial Dielectric Properties of Microscopic Metalized Filaments in Composites*, 70 (9) J.Appl. Phys. 4679 (1991). *Stockton* examined two size ranges of filaments, commercially available fibers with diameters near 10 μm, and self assembling microstructures, derived from organic surfactants, whose diameters were about twentyfold smaller. *Stockton* at 4679. *Stockton* noted that both high and low dielectric loss composites are possible depending on filament conductivity. *Id.* *Stockton* further noted that in a complex material such as the fiber/polymer there is a large number of experimental values – particle diameters, length distributions, aspect ratios, metallization thickness, conductivity, particle dispersion, clustering, alignment, polymer matrix dielectric properties, and density - that affect composite permittivities. *Id.* *Stockton* used metal films (e.g., nickel, copper, iron or permalloy) to create metalized tubules or fibers for use as the filaments to be embedded within the dielectric material. *Id.* at 4681.

[0014] Similarly, the effect of adding metalized tubules to an insulating polymer were examined by Browning et al. S.L. Browning et al., *Fabrication and Radio Frequency Characterization of High Dielectric Loss Tubule-Based Composites near Percolation,* 84 (11) J. Appl. Phys. 6109 (1998). *Browning* observed that when sufficient particles have been loaded the composite of tubules and polymers will begin to conduct over macroscopic distances. The onset of this transition is called percolation, and the volume loading of conducting particles at this point is termed the percolation threshold. *Browning* noted that percolation is accompanied by substantial changes in dielectric properties. *Browning* at 6109. *Browning* examined permittivities as a function of loading volume of the tubules. *Id.* at 6111.

[0015] Existing artificial dielectrics are limited in their application and use because they typically have relatively low dielectric constants and have fixed

dielectric constants at a particular frequency. These limitations, as discussed in *Stockton*, have been attributed to clumping of metallized fibers once the density of the fibers becomes high. When the metallized fibers clump, they lose their insulative characteristics and become conducting, thereby limiting the ability to achieve high dielectric constants within existing artificial dielectrics. Furthermore, dielectric structures based on existing dielectrics and dielectric structures are limited in their application.

[0016] What are needed are artificial dielectrics that have very high dielectric constants that can be statically or dynamically adjusted based on a wide range of potential applications.

Brief Summary of the Invention

[0017] Artificial dielectrics using nanowstructures, such as nanowires, are disclosed. In embodiments artificial dielectrics using nanorods, nanotubes, nanotetrapods and/or nanoribbons or other nanostructures are disclosed. The artificial dielectric includes a material (typically a dielectric) with a plurality of nanostructures, such as nanowires, embedded within the dielectric material. Very high dielectric constants can be achieved with an artificial dielectric using nanostructures. At the time of manufacturing, the dielectric constant can be adjusted by varying the length, shape, diameter, carrier density, aspect ratio, orientation and density of the nanostructures, for example, nanowires. Additionally, a controllable artificial dielectric using nanostructures, such nanowires, is disclosed in which the dielectric constant can be dynamically adjusted by applying an electric field to the controllable artificial dielectric.

[0018] A wide range of electronic devices can use artificial dielectrics with nanostructures to improve performance. Example devices include, but are not limited to, capacitors, thin film transistors, other types of thin film electronic devices, microstrip devices, surface acoustic wave (SAW) filters, other types of filters, and radar attenuating materials (RAM).

[0019] Artificial dielectrics using nanostructures within electronic devices can be used to improve the performance of cell phones, wireless personal digital assistants, 802.11 PC cards, global positioning satellites (GPS) receivers, and essentially any other apparatus that either receives or transmits radio waves. Furthermore, artificial dielectrics, and in particular, controllable dielectric materials using nanostructures can be used to significantly improve RAM and other coatings for stealth operation.

[0020] Further embodiments, features, and advantages of the invention, as well as the structure and operation of the various embodiments of the invention are described in detail below with reference to accompanying drawings.

Brief Description of the Figures

[0021] The accompanying drawings, which are incorporated herein and form a part of the specification, illustrate the present invention and, together with the description, further serve to explain the principles of the invention and to enable a person skilled in the pertinent art to make and use the invention.

[0022] FIG. 1A is a diagram of a single crystal semiconductor nanowire.

[0023] FIG. 1B is a diagram of a nanowire doped according to a core-shell structure.

[0024] FIG. 1C is a diagram of a nanowire that has a doped surface layer and an insulating coating.

[0025] FIG. 2A is a diagram of an artificial dielectric using nanowires, according to an embodiment of the invention.

[0026] FIG. 2B is a diagram of a side perspective of an artificial dielectric, according to an embodiment of the invention.

[0027] FIG. 3 is a diagram of a capacitor with an artificial dielectric using nanowires, according to an embodiment of the invention.

[0028] FIG. 4 is a diagram of a thin film transistor using an artificial dielectric with nanowires, according to an embodiment of the invention.

[0029] FIG. 5 is a plot that shows silicon nanowire lengths needed to achieve $\varepsilon_r = 300$ with a reasonable dissipation factor, according to embodiments of the invention.

[0030] FIG. 6A provides a chart of ε_r for an artificial dielectric with nanowires when σ equals $1e^5$, the nanowire length is 47.3 μm and the density is $1e^{15}$ nanowires/cm.^{3}

[0031] FIG. 6B provides a chart of the dissipation factor for an artificial dielectric with nanowires when σ equals $1e^5$, the nanowire length is 47.3 μm and the density is $1e^{15}$ nanowires/cm.^{3}

[0032] FIG. 7A provides a chart of ε_r for an artificial dielectric with nanowires when σ equals $1e^5$, the nanowire length is 20.7 μm and the density is $1e^{17}$ nanowires/cm.^{3}

[0033] FIG. 7B provides a chart of the dissipation factor for an artificial dielectric with nanowires when σ equals $1e^5$, the nanowire length is 20.7 μm and the density is $1e^{17}$ nanowires/cm.^{3}

[0034] FIG. 8A provides a chart of ε_r for an artificial dielectric with nanowires when σ equals $1e^5$, the nanowire length is 8.97 μm and the density is $1e^{18}$ nanowires/cm.^{3}

[0035] FIG. 8B provides a chart of the dissipation factor for an artificial dielectric with nanowires when σ equals $1e^5$, the nanowire length is 8.97 μm and the density is $1e^{18}$ nanowires/cm.^{3}

[0036] FIG. 9A provides chart of ε_r for an artificial dielectric using nanowires when σ equals $1e^5$, the nanowire length is 3.795 μm and the density is $1e^{19}$ nanowires/cm.^{3}

[0037] FIG. 9B provides chart of the dissipation factor for an artificial dielectric using nanowires when σ equals $1e^5$, the nanowire length is 3.795 μm and the density is $1e^{19}$ nanowires/cm.^{3}

[0038] FIG. 10 provides a diagram of an artificial dielectric using nanowires including electrodes, according to an embodiment of the present invention.

[0039] FIG. 11 provides a chart showing dielectric constant and loss characteristics for an artificial dielectric using nanowires for use in shielding and RAM applications, according to an embodiment of the invention.

[0040] FIG. 12 provides a plot of ε_r, ε_i, and the reflection coefficient using a three layer stack of artificial dielectrics with nanowires, according to an embodiment of the invention.

[0041] FIG. 13 provides a plot of ε_r, ε_i, and the reflection coefficient using a six layer stack of artificial dielectrics with nanowires, according to an embodiment of the invention.

[0042] FIG. 14 provides a diagram of an aircraft with a portion of the aircraft coated with a RAM that contains a controllable artificial dielectric using nanowires, according to an embodiment of the invention.

[0043] FIG. 15 provides a flowchart of a method for creating electronic devices with artificial dielectrics using nanowires, according to an embodiment of the invention.

[0044] FIG. 16 provides a method for creating electronic devices with artificial dielectrics using nanowires on an existing circuit board, according to an embodiment of the invention.

[0045] The present invention will now be described with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements. Additionally, the left-most digit(s) of a reference number identifies the drawing in which the reference number first appears.

Detailed Description of the Invention

[0046] It should be appreciated that the particular implementations shown and described herein are examples of the invention and are not intended to otherwise limit the scope of the present invention in any way. Indeed, for the sake of brevity, conventional electronics, manufacturing, semiconductor devices, and nanowire (NW), nanorod, nanotube, and nanoribbon technologies and other functional aspects of the systems (and components of the individual operating components of the systems) may not be described in detail herein. Furthermore, for purposes of brevity, the invention is frequently described herein as pertaining to nanowires, and to a semiconductor diode device.

[0047] Moreover, while a single nanowire is illustrated for the specific implementations discussed, the implementations are not intended to be limiting and a wide range of the number of nanowires and spacing can also be used. It should be appreciated that although nanowires are frequently referred to, the techniques described herein are also applicable to other nanostructures, such as nanorods, nanotubes, nanotetrapods, nanoribbons and/or combination thereof. It should further be appreciated that the manufacturing techniques described herein could be used to create any semiconductor device type, and other electronic component types. Further, the techniques would be suitable for application in electrical systems, optical systems, consumer electronics, industrial electronics, wireless systems, space applications, or any other application.

[0048] As used herein, an "aspect ratio" is the length of a first axis of a nanostructure divided by the average of the lengths of the second and third axes of the nanostructure, where the second and third axes are the two axes whose lengths are most nearly equal to each other. For example, the aspect ratio for a perfect rod would be the length of its long axis divided by the diameter of a cross-section perpendicular to (normal to) the long axis.

[0049] The term “heterostructure” when used with reference to nanostructures refers to nanostructures characterized by at least two different and/or

distinguishable material types. Typically, one region of the nanostructure comprises a first material type, while a second region of the nanostructure comprises a second material type. In certain embodiments, the nanostructure comprises a core of a first material and at least one shell of a second (or third etc.) material, where the different material types are distributed radially about the long axis of a nanowire, a long axis of an arm of a branched nanocrystal, or the center of a nanocrystal, for example. A shell need not completely cover the adjacent materials to be considered a shell or for the nanostructure to be considered a heterostructure; for example, a nanocrystal characterized by a core of one material covered with small islands of a second material is a heterostructure. In other embodiments, the different material types are distributed at different locations within the nanostructure; e.g., along the major (long) axis of a nanowire or along a long axis of arm of a branched nanocrystal. Different regions within a heterostructure can comprise entirely different materials, or the different regions can comprise a base material.

[0050] As used herein, a "nanostructure" is a structure having at least one region or characteristic dimension with a dimension of less than about 500 nm, e.g., less than about 200 nm, less than about 100 nm, less than about 50 nm, or even less than about 20 nm. Typically, the region or characteristic dimension will be along the smallest axis of the structure. Examples of such structures include nanowires, nanorods, nanotubes, branched nanocrystals, nanotetrapods, tripods, bipods, nanocrystals, nanodots, quantum dots, nanoparticles, branched tetrapods (e.g., inorganic dendrimers), and the like. Nanostructures can be substantially homogeneous in material properties, or in certain embodiments can be heterogeneous (*e.g.* heterostructures). Nanostructures can be, e.g., substantially crystalline, substantially monocrystalline, polycrystalline, amorphous, or a combination thereof. In one aspect, each of the three dimensions of the nanostructure has a dimension of less than about 500 nm, e.g., less than about 200 nm, less than about 100 nm, less than about 50 nm, or even less than about 20 nm.

[0051] As used herein, the term "nanowire" generally refers to any elongated conductive or semiconductive material (or other material described herein)

that includes at least one cross sectional dimension that is less than 500nm, and preferably, less than 100 nm, and has an aspect ratio (length:width) of greater than 10, preferably greater than 50, and more preferably, greater than 100.

[0052] The nanowires of this invention can be substantially homogeneous in material properties, or in certain embodiments can be heterogeneous (*e.g.* nanowire heterostructures). The nanowires can be fabricated from essentially any convenient material or materials, and can be, e.g., substantially crystalline, substantially monocrystalline, polycrystalline, or amorphous. Nanowires can have a variable diameter or can have a substantially uniform diameter, that is, a diameter that shows a variance less than about 20% (e.g., less than about 10%, less than about 5%, or less than about 1%) over the region of greatest variability and over a linear dimension of at least 5 nm (e.g., at least 10 nm, at least 20 nm, or at least 50 nm). Typically the diameter is evaluated away from the ends of the nanowire (*e.g.* over the central 20%, 40%, 50%, or 80% of the nanowire). A nanowire can be straight or can be e.g. curved or bent, over the entire length of its long axis or a portion thereof. In certain embodiments, a nanowire or a portion thereof can exhibit two- or three-dimensional quantum confinement. Nanowires according to this invention can expressly exclude carbon nanotubes, and, in certain embodiments, exclude "whiskers" or "nanowhiskers", particularly whiskers having a diameter greater than 100 nm, or greater than about 200 nm.

[0053] Examples of such nanowires include semiconductor nanowires as described in Published International Patent Application Nos. WO 02/17362, WO 02/48701, and WO 01/03208, carbon nanotubes, and other elongated conductive or semiconductive structures of like dimensions, which are incorporated herein by reference.

[0054] As used herein, the term "nanorod" generally refers to any elongated conductive or semiconductive material (or other material described herein) similar to a nanowire, but having an aspect ratio (length:width) less than that of a nanowire. Note that two or more nanorods can be coupled together along their longitudinal axis so that the coupled nanorods span all the way between

electrodes. Alternatively, two or more nanorods can be substantially aligned along their longitudinal axis, but not coupled together, such that a small gap exists between the ends of the two or more nanorods. In this case, electrons can flow from one nanorod to another by hopping from one nanorod to another to traverse the small gap. The two or more nanorods can be substantially aligned, such that they form a path by which electrons can travel between electrodes.

[0055] A wide range of types of materials for nanowires, nanorods, nanotubes and nanoribbons can be used, including semiconductor material selected from, e.g., Si, Ge, Sn, Se, Te, B, C (including diamond), P, B-C, B-P(BP6), B-Si, Si-C, Si-Ge, Si-Sn and Ge-Sn, SiC, BN/BP/BAs, AlN/AlP/AlAs/AlSb, GaN/GaP/GaAs/GaSb, InN/InP/InAs/InSb, BN/BP/BAs, AlN/AlP/AlAs/AlSb, GaN/GaP/GaAs/GaSb, InN/InP/InAs/InSb, ZnO/ZnS/ZnSe/ZnTe, CdS/CdSe/CdTe, HgS/HgSe/HgTe, BeS/BeSe/BeTe/MgS/MgSe, GeS, GeSe, GeTe, SnS, SnSe, SnTe, PbO, PbS, PbSe, PbTe, CuF, CuCl, CuBr, CuI, AgF, AgCl, AgBr, AgI, BeSiN2, CaCN2, ZnGeP2, CdSnAs2, ZnSnSb2, CuGeP3, CuSi2P3, (Cu, Ag)(Al, Ga, In, Tl, Fe)(S, Se, Te) 2, Si3N4, Ge3N4, Al2O3, (Al, Ga, In) 2 (S, Se, Te) 3, Al2CO, and an appropriate combination of two or more such semiconductors.

[0056] The nanowires can also be formed from other materials such as metals such as gold, nickel, palladium, iradium, cobalt, chromium, aluminum, titanium, tin and the like, metal alloys, polymers, conductive polymers, ceramics, and/or combinations thereof. Other now known or later developed conducting or semiconductor materials can be employed.

[0057] In certain aspects, the semiconductor may comprise a dopant from a group consisting of: a p-type dopant from Group III of the periodic table; an n-type dopant from Group V of the periodic table; a p-type dopant selected from a group consisting of: B, Al and In; an n-type dopant selected from a group consisting of: P, As and Sb; a p-type dopant from Group II of the periodic table; a p-type dopant selected from a group consisting of: Mg, Zn, Cd and Hg; a p-type dopant from Group IV of the periodic table; a p-type dopant selected from a group consisting of: C and Si.; or an n-type dopant selected

from a group consisting of: Si, Ge, Sn, S, Se and Te. Other now known or later developed dopant materials can be employed.

[0058] Additionally, the nanowires or nanoribbons can include carbon nanotubes, or nanotubes formed of conductive or semiconductive organic polymer materials, (e.g., pentacene, and transition metal oxides).

[0059] Hence, although the term "nanowire" is referred to throughout the description herein for illustrative purposes, it is intended that the description herein also encompass the use of nanotubes (e.g., nanowire-like structures having a hollow tube formed axially therethrough). Nanotubes can be formed in combinations/thin films of nanotubes as is described herein for nanowires, alone or in combination with nanowires, to provide the properties and advantages described herein.

[0060] It should be understood that the spatial descriptions (e.g., "above", "below", "up", "down", "top", "bottom", etc.) made herein are for purposes of illustration only, and that devices of the present invention can be spatially arranged in any orientation or manner.

[0061] There are many advantages of nanowires compared to standard semiconductors, including the use of insulating, flexible, or low-loss substrates, cost, and the ability to integrate nanowires into large structures. The present invention is directed to methods which apply these advantages to artificial dielectrics using nanowires. While the examples and discussion provided focus on nanowires, nanotubes, nanorods, and nanoribbons can also be used.

Artificial Dielectric Using Nanowires Embodiments

[0062] FIG. 1A illustrates a single crystal semiconductor nanowire core (hereafter "nanowire") 100. FIG. 1A shows a nanowire 100 that is a uniformly doped single crystal nanowire. Such single crystal nanowires can be doped into either p- or n-type semiconductors in a fairly controlled way. Doped nanowires such as nanowire 100 exhibit improved electronic properties. For

instance, such nanowires can be doped to have carrier mobility levels comparable to bulk single crystal materials.

[0063] FIG. 1B shows a nanowire 110 doped according to a core-shell structure. As shown in FIG. 1B, nanowire 110 has a doped surface layer 112, which can have varying thickness levels, including being only a molecular monolayer on the surface of nanowire 110.

[0064] The valence band of the insulating shell can be lower than the valence band of the core for p-type doped wires, or the conduction band of the shell can be higher than the core for n-type doped wires. Generally, the core nanostructure can be made from any metallic or semiconductor material, and the shell can be made from the same or a different material. For example, the first core material can comprise a first semiconductor selected from the group consisting of: a Group II-VI semiconductor, a Group III-V semiconductor, a Group IV semiconductor, and an alloy thereof. Similarly, the second material of the shell can comprise a second semiconductor, the same as or different from the first semiconductor, e.g., selected from the group consisting of: a Group II-VI semiconductor, a Group III-V semiconductor, a Group IV semiconductor, and an alloy thereof. Example semiconductors include, but are not limited to, CdSe, CdTe, InP, InAs, CdS, ZnS, ZnSe, ZnTe, HgTe, GaN, GaP, GaAs, GaSb, InSb, Si, Ge, AlAs, AlSb, PbSe, PbS, and PbTe. As noted above, metallic materials such as gold, chromium, tin, nickel, aluminum etc. and alloys thereof can be used as the core material, and the metallic core can be overcoated with an appropriate shell material such as silicon dioxide or other insulating materials

[0065] Nanostructures can be fabricated and their size can be controlled by any of a number of convenient methods that can be adapted to different materials. For example, synthesis of nanocrystals of various composition is described in, e.g., Peng et al. (2000) "Shape Control of CdSe Nanocrystals" Nature 404, 59-61; Puntes et al. (2001) "Colloidal nanocrystal shape and size control: The case of cobalt" Science 291, 2115-2117; USPN 6,306,736 to Alivisatos et al. (October 23, 2001) entitled "Process for forming shaped group III-V semiconductor nanocrystals, and product formed using process";

USPN 6,225,198 to Alivisatos et al. (May 1, 2001) entitled "Process for forming shaped group II-VI semiconductor nanocrystals, and product formed using process"; USPN 5,505,928 to Alivisatos et al. (April 9, 1996) entitled "Preparation of III-V semiconductor nanocrystals"; USPN 5,751,018 to Alivisatos et al. (May 12, 1998) entitled "Semiconductor nanocrystals covalently bound to solid inorganic surfaces using self-assembled monolayers"; USPN 6,048,616 to Gallagher et al. (April 11, 2000) entitled "Encapsulated quantum sized doped semiconductor particles and method of manufacturing same"; and USPN 5,990,479 to Weiss et al. (November 23, 1999) entitled "Organo luminescent semiconductor nanocrystal probes for biological applications and process for making and using such probes."

[0066] Growth of nanowires having various aspect ratios, including nanowires with controlled diameters, is described in, e.g., Gudiksen et al (2000) "Diameter-selective synthesis of semiconductor nanowires" J. Am. Chem. Soc. 122, 8801-8802; Cui et al. (2001) "Diameter-controlled synthesis of single-crystal silicon nanowires" Appl. Phys. Lett. 78, 2214-2216; Gudiksen et al. (2001) "Synthetic control of the diameter and length of single crystal semiconductor nanowires" J. Phys. Chem. B 105,4062-4064; Morales et al. (1998) "A laser ablation method for the synthesis of crystalline semiconductor nanowires" Science 279, 208-211; Duan et al. (2000) "General synthesis of compound semiconductor nanowires" Adv. Mater. 12, 298-302; Cui et al. (2000) "Doping and electrical transport in silicon nanowires" J. Phys. Chem. B 104, 5213-5216; Peng et al. (2000) "Shape control of CdSe nanocrystals" Nature 404, 59-61; Puntes et al. (2001) "Colloidal nanocrystal shape and size control: The case of cobalt" Science 291, 2115-2117; USPN 6,306,736 to Alivisatos et al. (October 23, 2001) entitled "Process for forming shaped group III-V semiconductor nanocrystals, and product formed using process"; USPN 6,225,198 to Alivisatos et al. (May 1, 2001) entitled "Process for forming shaped group II-VI semiconductor nanocrystals, and product formed using process"; USPN 6,036,774 to Lieber et al. (March 14, 2000) entitled "Method of producing metal oxide nanorods"; USPN 5,897,945 to Lieber et al. (April 27, 1999) entitled "Metal oxide nanorods"; USPN 5,997,832 to

Lieber et al. (December 7, 1999) "Preparation of carbide nanorods"; Urbau et al. (2002) "Synthesis of single-crystalline perovskite nanowires composed of barium titanate and strontium titanate" J. Am. Chem. Soc., 124, 1186; and Yun et al. (2002) "Ferroelectric Properties of Individual Barium Titanate Nanowires Investigated by Scanned Probe Microscopy" Nanoletters 2, 447.

[0067] Growth of branched nanowires (e.g., nanotetrapods, tripods, bipods, and branched tetrapods) is described in, e.g., Jun et al. (2001) "Controlled synthesis of multi-armed CdS nanorod architectures using monosurfactant system" J. Am. Chem. Soc. 123, 5150-5151; and Manna et al. (2000) "Synthesis of Soluble and Processable Rod-,Arrow-, Teardrop-, and Tetrapod-Shaped CdSe Nanocrystals" J. Am. Chem. Soc. 122, 12700-12706.

[0068] Synthesis of nanoparticles is described in, e.g., USPN 5,690,807 to Clark Jr. et al. (November 25, 1997) entitled "Method for producing semiconductor particles"; USPN 6,136,156 to El-Shall, et al. (October 24, 2000) entitled "Nanoparticles of silicon oxide alloys"; USPN 6,413,489 to Ying et al. (July 2, 2002) entitled "Synthesis of nanometer-sized particles by reverse micelle mediated techniques"; and Liu et al. (2001) "Sol-Gel Synthesis of Free-Standing Ferroelectric Lead Zirconate Titanate Nanoparticles" J. Am. Chem. Soc. 123, 4344. Synthesis of nanoparticles is also described in the above citations for growth of nanocrystals, nanowires, and branched nanowires, where the resulting nanostructures have an aspect ratio less than about 1.5.

[0069] Synthesis of core-shell nanostructure heterostructures, namely nanocrystal and nanowire (e.g., nanorod) core-shell heterostructures, are described in, e.g., Peng et al. (1997) "Epitaxial growth of highly luminescent CdSe/CdS core/shell nanocrystals with photostability and electronic accessibility" J. Am. Chem. Soc. 119, 7019-7029; Dabbousi et al. (1997) "(CdSe)ZnS core-shell quantum dots: Synthesis and characterization of a size series of highly luminescent nanocrysallites" J. Phys. Chem. B 101, 9463-9475; Manna et al. (2002) "Epitaxial growth and photochemical annealing of graded CdS/ZnS shells on colloidal CdSe nanorods" J. Am. Chem. Soc. 124, 7136-7145; and Cao et al. (2000) "Growth and properties of semiconductor

core/shell nanocrystals with InAs cores" J. Am. Chem. Soc. 122, 9692-9702. Similar approaches can be applied to growth of other core-shell nanostructures.

[0070] Growth of nanowire heterostructures in which the different materials are distributed at different locations along the long axis of the nanowire is described in, e.g., Gudiksen et al. (2002) "Growth of nanowire superlattice structures for nanoscale photonics and electronics" Nature 415, 617-620; Bjork et al. (2002) "One-dimensional steeplechase for electrons realized" Nano Letters 2, 86-90; Wu et al. (2002) "Block-by-block growth of single-crystalline Si/SiGe superlattice nanowires" Nano Letters 2, 83-86; and US patent application 60/370,095 (April 2, 2002) to Empedocles entitled " Nanowire heterostructures for encoding information." Similar approaches can be applied to growth of other heterostructures.

[0071] In certain embodiments, the collection or population of nanostructures employed in the artificial dielectric is substantially monodisperse in size and/or shape. See, e.g., US patent application 20020071952 by Bawendi et al entitled "Preparation of nanocrystallites."

[0072] FIG. 1C shows a nanowire 120 that is doped with a doped surface layer 112 according to the core-shell structure shown in FIG. 1B, and is also coated with an insulator layer 114.

[0073] An artificial dielectric can be created by embedding nanostructures, such as nanowires (and/or other nanostructures), in a material, such as a dielectric material. FIG. 2A illustrates artificial dielectric 200, according to an embodiment of the invention. Artificial dielectric 200 includes dielectric material 205 and nanostructures, such as nanowires, for example, nanowires 210. FIG. 2B illustrates a side perspective of artificial dielectric 200, according to an embodiment of the invention. The side perspective illustrates the embedded nature of the nanowires throughout the dielectric material. The nanowires can be embedded in a wide range of dielectric materials, including but not limited solid dielectrics, such as plastics, metal oxides, glasses, semiconductors (e.g., silicon), and pure single crystals (e.g., diamond, sapphire, quartz) as well as those described above and in R. Bartnikas,

Dielectrics and Insulators, in The Electrical Engineering Handbook 1143-1150 (Michael C. Dorf, ed. CRC Press 1993). The dielectric materials can include both liquid and solid dielectric materials. The dielectric material may include one or more fillers such as fine particle sized powdered materials (e.g., mica, silica, glass, and wood flour) to improve physical properties, or may be made from a composite or mixture of materials formulated to a specific dielectric constant or loss tangent, for example.

[0074] In embodiments the nanowires can be metals, silicon, semiconductors or other materials and material combinations as described above for nanowires, nanorods, nanotubes, nanotetrapods, or nanoribbons. The nanowires can be embedded in a dielectric in the form of a matrix or in a thin film. The nanowires can be distributed within the artificial dielectric isotropically or anisotropically.

[0075] The dielectric constant of artificial dielectric 200 can be adjusted by varying the length, diameter, carrier density, shape, aspect ratio, orientation and density of the nanowires, such as nanowire 210. When silicon nanowires are used, a silicon oxide insulator can be created around the nanowire. This avoids the percolation problems of artificial dielectrics that use metalized fibers.

[0076] The resulting artificial dielectric can have an extremely large dielectric constant, and can be coated onto a surface, formed into a film or shaped into a wide variety of other configurations. Artificial dielectrics can also have dielectric constants that are dynamically controllable. By applying an electric field to a film of an artificial dielectric, it is possible to modulate the carrier density in the wires within the artificial dielectric by accumulation or inversion in the nanowires. Therefore, the electric field modulates the dielectric constant and reflectivity at an interface. In fact, by using oriented nanowires, the dielectric constant can be a function of polarization in that if the electric vector is aligned with the nanowires, the artificial dielectric comes into play. This, in turn, leads to a polarization-dependent change in reflectivity. That is, the artificial dielectric only changes reflectance if it is probed with the correct polarization.

[0077] The electric field can be DC, AC or pulse modulated to convey information. The pulse modulation could be a pseudo random sequence, so that the received beam has to be despread to come up out of the noise. The electric field can be applied with film or other electrodes on the top and bottom of the film, or by using the fringing fields from electrodes on one side, for example.

Artificial Dielectric Using Nanowire Component Applications

[0078] A wide range of potential applications exist for the use of an artificial dielectric with nanowires. Example devices include, but are not limited to, capacitors, thin film transistors, other types of thin film electronic devices, microstrip devices, surface acoustic wave (SAW) filters, other types of filters, and radar attenuating materials (RAM). Several exemplary embodiments are provided herein. These are not intended to limit the scope of the invention, but rather to show a wide range of examples to demonstrate the broad applicability of the invention to a wide range of devices.

[0079] FIG 3 illustrates capacitor 300 with an artificial dielectric using nanowires, according to an embodiment of the invention. Capacitor 300 includes two capacitor plates 310 and 320. Capacitor plate characteristics and materials are well known by individuals skilled in the relevant arts. Sandwiched between the two capacitor plates is an artificial dielectric including dielectric material 330 and nanowires, such as nanowire 340. When used voltage is applied across capacitor plates 310 and 320 in a conventional manner. Dielectric material 330 can be a typical dielectric material used in capacitors, as will be known by individuals skilled in the relevant arts, but is not limited to typical materials. In this application, to maximize the dielectric constant the nanowires should be perpendicular to the capacitor plates 310 and 310, which are roughly parallel to one another. Other nanowire orientations and capacitor plates can be used, albeit with reduced dielectric constants. By using an artificial dielectric within a capacitor, the dielectric constant can be raised by a factor of 100 over dielectrics used in existing capacitor. As a

result, space needs for capacitors within electronics can significantly be reduced.

[0080] FIG. 4 is a diagram of thin film transistor 400 with an artificial dielectric using nanowires, according to an embodiment of the invention. Thin film transistor 400 includes substrate 410, gate electrode 420, dielectric film 430, semiconducting film 440, source electrode 460 and drain electrode 450. An artificial dielectric is created by embedding nanorods, such as nanorod 470 in dielectric film 430. Copending, commonly owned U.S. Patent Application No. 10/674,060, entitled *Large Area Nanoenabled Macroelectronic Substrates and Uses Thereof*, filed by Duan on Sep. 30, 2003, which is herein incorporated by reference in its entirety, provide thin films for use as semiconducting film 440, for example.

[0081] The use of a high dielectric constant artificial dielectric as the gate dielectric of a thin film transistor can significantly increase the transistor's performance. Thin film transistors on plastic or inorganic substrates, such as substrate 410, require a dielectric thin film for the gate dielectric. In FIG. 4 the gate dielectric is represented by the area containing dielectric film 430 and nanowires 470. As is well known by individuals skilled in the art, increased capacitive coupling from the gate electrode, such as gate electrode 420, to the semiconducting channel, represented in FIG. 4 by the area containing semiconducting film 440, improves the transistor performance. One standard technique for increasing capacitive coupling is to reduce the thickness of the dielectric film between the semiconducting channel and the gate electrode.

[0082] However, for many types of processing envisioned for thin-film transistor fabrication (e.g., coating or printing processes), it is not possible to reduce the film thickness beyond a certain point. The present invention addresses this problem by introducing an artificial dielectric film, such as is created when nanorods 470 are embedded in dielectric film 430.

[0083] The artificial dielectric film uses an insulating polymer film for which the dielectric constant has been enhanced by embedding semiconducting or metallic nanorods in the polymer matrix. The effect of the embedded nanowires is to increase the effective dielectric constant of the film, thereby

providing the same capacitive coupling as a thinner film of conventional dielectric material. Thus, the use of the artificial dielectric with nanowires allows high performance transistors to be built with thicker films compared to a conventional dielectric, allowing for high volume and low cost fabrication processes that would be desirable with plastic substrates.

[0084] Referring to FIG. 4, in an embodiment substrate 410 can be made of polyethylenenaphthalate (PEN). Gate electrode 420, drain electrode 450 and source electrode 460 can be made from a conducting polymer, such as polyaniline, or they may be metallic. Nanorods, such as nanorod 470, can be made from silicon or other semiconducting materials. Metallic nanorods would also be effective for increasing the dielectric constant. If silicon nanorods are used, they may be doped with arsenic, phosphorus, boron or other dopants to increase the conductivity. If different types of semiconducting materials are used, other dopants may be used.

[0085] For artificial dielectric 480 to be a good insulator it may be necessary to encapsulate nanorods, such as nanorod 470, in an insulating film, such as an oxide. The insulator will prevent the nanorods from acting as a conducting path through dielectric film 430. Dielectric film 430 can be made of polyimide. Semiconducting film 440 can be made of pentacene. The materials for each of the elements of thin film transistor are provided for illustrative purposes and are not intended to limit the scope of the invention. Based on the teachings herein, other materials for use in thin film transistor 500 will be known to individuals skilled in the relevant arts.

[0086] While thin-film transistor 400 is used to demonstrate the use of an artificial dielectric, many other device configurations can benefit from the higher dielectric constant of artificial dielectric 480. The thin-film transistor 400 structure is illustrative, and not intended to limit the scope of the invention.

[0087] FIG. 5 provides a plot that shows silicon nanowire lengths needed to achieve $\varepsilon_r = 300$ with a reasonable dissipation factor, according to embodiments of the invention. This range of the parameters in FIG. 5 are applicable to the use of artificial dielectrics with nanowires in electronic

components, such as microstrip devices, SAW filters, capacitors, thin-film devices, etc. The chart plots the length of wire and the maximum frequency that an artificial dielectric using nanowires of that particular length could be used at while keeping the dissipation factor below 0.05. The conductivity of the nanowires is $1e^5$. So, for example, referring to FIG. 5, as shown by point 510 and 512 for a nanowire density of $1e^{16}$ nanowires/cm^3, the length of the nanowires would need to be about 47.3 μm to achieve ε_r = 300 with a dissipation factor of 0.05. The maximum frequency that these parameters could be used would be less than 1 Ghz before the dissipation factor becomes greater than 0.05.

[0088] Similarly, as shown by points 520 and 522 for a nanowire density of $1e^{17}$ nanowires/cm^3, the length of the nanowires would need to be about 20.7 μm to achieve ε_r = 300 with a dissipation factor of 0.05. The maximum frequency that these parameters could be used would also be less than 1 Ghz. As shown by points 530 and 532 for a nanowire density of $1e^{18}$ nanowires/cm^3, the length of the nanowires would need to be about 8.97 μm to achieve ε_r = 300 with a dissipation factor of 0.05. The maximum frequency that these parameters could be used would be about 3 Ghz. As shown by points 540 and 542 for a nanowire density of $1e^{19}$ nanowires/cm^3, the length of the nanowires would need to be about 3.795 μm to achieve ε_r = 300 with a dissipation factor of 0.05. The maximum frequency that these parameters could be used would be about 10 Ghz.

[0089] FIGs. 6-9 provide charts of ε_r and the dissipation factor (which can also be referred to as the loss tangent) for each of the above combinations of nanowire densities and lengths, according to embodiments of the invention.

[0090] FIGs. 6A and 6B provide charts of ε_r and the dissipation factor, respectively, when the conductivity, σ, equals $1e^5$, the nanowire length is 47.3 μm and the density is $1e^{15}$ nanowires/$cm.^3$ The charts illustrate the value of ε_r and the dissipation factor over a range of frequencies. FIG. 6B shows that at a frequency of about 10Mhz the dissipation factor begins to rise significantly, and reaches a dissipation factor value of 0.05 at about 100Mhz. The

significance of this is that for this set of factors an ε_r of 300 is attainable with a reasonable dissipation factor up to about 100Mhz.

[0091] FIGs. 7A and 7B provide charts of ε_r and the dissipation factor, respectively, when σ equals $1e^5$, the nanowire length is 20.7 μm and the density is $1e^{17}$ nanowires/cm.^{3} The charts illustrate the value of ε_r and the dissipation factor over a range of frequencies. FIG. 7B shows that at a frequency of about 50Mhz the dissipation factor begins to rise significantly, and reaches a dissipation factor value of 0.05 at about 500Mhz. The significance of this is that for this set of factors an ε_r of 300 is attainable with a reasonable dissipation factor up to about 500Mhz.

[0092] FIGs. 8A and 8B provide charts of ε_r and the dissipation factor, respectively, when σ equals $1e^5$, the nanowire length is 8.97 μm and the density is $1e^{18}$ nanowires/cm.^{3} The charts illustrate the value of ε_r and the dissipation factor over a range of frequencies. FIG. 8B shows that at a frequency of about 100Mhz the dissipation factor begins to rise significantly, and reaches a dissipation factor value of 0.05 at about 1Ghz. The significance of this is that for this set of factors an ε_r of 300 is attainable with a reasonable dissipation factor up to about 1Ghz.

[0093] FIGs. 9A and 9B provide charts of ε_r and the dissipation factor, respectively, when σ equals $1e^5$, the nanowire length is 3.795 μm and the density is $1e^{19}$ nanowires/cm.^{3} The charts illustrate the value of ε_r and the dissipation factor over a range of frequencies. FIG. 9B shows that at a frequency of about 500Mhz the dissipation factor begins to rise significantly, and reaches a dissipation factor value of 0.05 at about 10Ghz. The significance of this is that for this set of factors an ε_r of 300 is attainable with a reasonable dissipation factor up to about 10Ghz.

[0094] Collectively, the charts illustrated in FIGs. 6-9 show that at 10Ghz, ε_r = 300 that low loss operation requires relatively short nanowires and high densities of nanowires. The charts further demonstrate that low loss region extends higher in frequency for denser and shorter mixtures of nanowires embedded within a dielectric material. FIGs. 6-9 focus on artificial dielectric

considerations that most likely would have component applications (e.g., capacitors, thin film transistors, microstrips, SAW filters, etc).

[0095] FIG. 10 illustrates artificial dielectric 1000 including electrodes, according to an embodiment of the present invention. Artificial dielectric includes dielectric material 205, nanowires, such as nanowire 210, and electrodes 1010A and 1010B. As discussed above, a voltage can be applied across electrodes 1010A and 1010B to dynamically adjust the dielectric constant. Many different configurations of an artificial dielectric with electrodes are possible. For example, plates can be positioned along portions or entire edges of an opposite sides of artificial dielectric. Plates also may be positioned in a manner similar to those illustrated in FIG. 3. Other configurations will be apparent to individuals skilled in the relevant arts based on the teachings herein.

[0096] Artificial dielectrics with nanowires can also be used for shielding applications or radar absorbing materials (RAM). In these applications a have high loss within the artificial dielectric is desirable. Depending on the other characteristics of the artificial dielectric, the loss characteristics of a film of the artificial dielectric can be controlled. For example, one artificial dielectric composition could be transparent at optical wavelengths, so the material is clear and therefore well camouflaged when spread over the ground. This same material could also be made to be transparent to the frequencies that it is being probed with if they are not optical (e.g., RF frequencies).

[0097] In another example, the artificial dielectric coating could be made to be absorptive to a probe wavelength. Alternatively, the artificial dielectric coating can be formulated to be a low observable radar material until an electric field is applied, at which time the artificial dielectric material will reflect a given wavelength or set of wavelengths.

[0098] Moreover, the reflection coefficient of a material could be greatly increased by embedding the material between two layers of 50% and 100% reflectivity. If the phase through the artificial dielectric is 90 degrees the front and rear reflections cancel. If the phase is not 90 degrees, then they cancel imperfectly. Achieving ten percent modulation depth is likely to be

straightforward. Also, these could be used as the surfaces of a corner cube, so the reflection would only occur back towards the emitter, and the strength would be much higher. Nanowires can be coated on the sides of a corner cube, or embedded between reflective or partially reflective layers. They can be part of an optical system (e.g., between combinations of quarter-wave or half wave plates and reflectors to make a circularly polarized reflector.)

[0099] FIG. 11 provides dielectric constant and loss characteristics for an artificial dielectric using nanowires for use in shielding and RAM applications, according to an embodiment of the invention. As indicated above, very high dielectric coefficients can be achieved. FIG 11 provides data for artificial dielectrics that would more likely be used in such applications as stealth coatings and other RAM materails. FIG. 11 provides plots of ε_r and ε_i for an artificial dielectric in which there are 10^{16} nanowires/m^3 over a range of conductivities and nanowire lengths. The nanowires are 100 nm in diameter.

[00100] The charts show ε_r and ε_i over a wide range of nanowire lengths and conductivities. Nanowire length is plotted along the x-axis, conductivity is plotted along the y-axis and ε_r and ε_i are plotted along a z-axis. The charts show that when the nanowires are heavily doped with a relatively high conductivity of 10^5 S/m and have a length of about 100 microns that ε_r is 2500 and ε_i is 1400 at a particular frequency with a short wavelength. These represent a very high dielectric constant with a short wavelength and a very high loss. Thus, if one were trying to make a low observable radar coating for an airplane, for example, that absorbs radar waves the material would have tremendously high loss and could be mixed with a magnetic material that was also high loss. An incoming electromagnetic wave could be attenuated quickly in such a material because the impedance of the artificial dielectric and metal could be approximately matched. Additionally, by mixing the lossy magnetic material with the lossy artificial dielectric, such that the square root of the ratio of μ/ε_r is close to that of free space, reflections at the boundary between the coating and air can be eliminated to support stealth operation.

[00101] A simulation was conducted to demonstrate the use of artificial dielectrics using nanowires within RAM materials. In the simulation, a three

layer stack or artificial dielectrics using nanowires that totaled 12mm thick was assumed. The dielectric matrix used to create the artificial dielectric had an $\varepsilon_r = 2.8$ and was a low loss material. It was also assumed that the dielectric matrix would have a magnetic permeability of 30. The nanowires that were embedded in the dielectric matrix to create the artificial dielectric were assumed to be 20 μm long, 100 nm diameter silicon doped nanowires. The nanowire volume fraction within the artificial dielectric was less than 1%. The substrate used was metal.

[00102] FIG. 12 provides a plot of ε_r, ε_i, and the reflection coefficient using a the three layer stack arrangement described above. The key determination to note is that the reflection coefficient remains about 0 for frequencies above about 1 Ghz. In the plots for ε_r and ε_i, the three curves correspond with each of the three layers in the stack.

[00103] FIG. 13 provides a similar plot of ε_r, ε_i, and the reflection coefficient using a six layer stack arrangement with the same parameters as above. In this case the total thickness would be approximately 24mm. The key point to observe within FIG. 13 is that the reflection coefficient remains closer to 0 than in the three layer simulation, and is about 0 for frequencies above about 1 Mhz. In the plots for ε_r and ε_i, the six curves correspond with each of the six layers in the stack.

[00104] FIG. 14 illustrates aircraft 1400 with a portion of the aircraft coated with a RAM that contains a controllable artificial dielectric using nanowires, according to an embodiment of the invention. Aircraft 1400 is primarily covered with RAM coating 1410. RAM coating 1410 can be a traditional RAM material or a RAM material that includes an artificial dielectric using nanowires as described with respect to FIGs. 12 and 13. RAM coating 1420 is a RAM material using a controllable artificial dielectric using nanowires. The reflectivity of RAM coating 1420 can be adjusted by applying an electric field to the artificial dielectric using nanowires. RAM coating 1420 would typically be used as a coating over areas in which aircraft 1400 had signal transmitting and/or receiving equipment. FIG. 14 illustrates RAM coating 1420 along a side of aircraft 1400. This position is not intended to limit the

invention. RAM coating 1420 could be located in a wide variety of positions including, but not limited to the tail or nose of an aircraft.

[00105] When aircraft 1400 does not need to transmit or receive particular type or types signals, no electric field would be applied to RAM coating 1420. When aircraft 1400 needs to transmit or receive such a signal or signals, an electric field could be applied to the artificial dielectric using nanowires within RAM coating 1420 to change the reflectivity of RAM coating 1420 to momentarily permit the signal or signals to be sent or received. This allows aircraft 1420 to transmit and receive a signal or signals at one or more frequencies (e.g., the electric field could be adjusted so that signals would be transmitted at random frequencies), while minimizing the likelihood of being detected and maintaining stealth operation. The RAM coating using a controllable artificial dielectric using nanowires could be applied to a wide range of vehicles (e.g., aircraft, ships, trucks, tanks, etc.) or enclosures (e.g., secure bunkers, radar sites, etc.).

Methods of Making Devices with Artificial Dielectrics using Nanowires

[00106] The scope of the invention covers many methods of making devices using artificial dielectrics using nanowires. For the ease of illustration, only two methods are described herein. These are not intended to limit the scope of the application, but rather demonstrate the broad scope of the invention.

[00107] Many methods of making devices using artificial dielectrics using nanowiresFIG. 15 provides a method 1500 for creating electronic devices with artificial dielectrics using nanowires, according to an embodiment of the invention. Method 1500 could be used to create devices such as microstrip filters, SAW filters, capacitors and the like onto a circuit board for use in a wide variety of applications, such as cell phones, wireless communications cards and the like.

[00108] Method 1500 begins in step 1510. In step 1510 nanowires are mixed into a polymer to create an artificial dielectric with nanowires. The specific types of nanowires, along with the density, diameter, doping and other

characteristics would be determined based on the specific application and charts similar to those presented in FIG. 6 above, for example. In step 1520, the artificial dielectric is extruded into a thin film. In step 1530 copper (or other conductor) is applied to the top and bottom of the thin film. In step 1540 the copper is patterned based on the properties of the desired device to be produced. In step 1550, method 1500 ends.

[00109] FIG. 16 provides method 1600 for creating electronic devices with artificial dielectrics using nanowires on an existing circuit board, according to an embodiment of the invention. Method 1600 could be used to create devices such as microstrip filters, SAW filters, capacitors and the like onto a circuit board for use in a wide variety of applications, such as cell phones, wireless communications cards, and the like.

[00110] Method 1600 begins in step 1610. In step 1610 nanowires are mixed into a polymer to create an artificial dielectric with nanowires. The specific types of nanowires, along with the density, diameter, doping and other characteristics would be determined based on the specific application and charts similar to those presented in FIG. 6 above, for example. In step 1620, the artificial dielectric is extruded into a thin film. In step 1630 the thin film of artificial dielectric with nanowires is applied to selected areas of an existing circuit board where devices using the artificial dielectric are desired. In step 1640 electrical connections are provided to the areas where the artificial dielectric was applied, as needed. In step 1650 a optional ground plane is provide above the artificial dielectric. In some embodiments, the ground plan could simply be the casing of the device, for example, a cell phone enclosure. In step 1660, method 1600 ends.

Conclusion

[00111] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention. Thus, the breadth

and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is Claimed Is:

1. An artificial dielectric, comprising:
   (a) a dielectric; and
   (b) a plurality of nanostructures embedded in said dielectric.

2. The artificial dielectric of claim 1, wherein said nanostructures comprise nanowires.

3. The artificial dielectric of claim 1, wherein said nanostructures comprise silicon nanowires.

4. The artificial dielectric of claim 3, wherein said nanowires comprise an insulating shell comprising an oxide, carbide or nitride coating.

5. The artificial dielectric of claim 2, wherein said nanowires are disposed with isotropic orientations within said dielectric.

6. The artificial dielectric of claim 2, wherein said nanowires are disposed with anisotropic orientations within said dielectric.

7. The artificial dielectric of claim 1, wherein said dielectric comprises a liquid.

8. The artificial dielectric of claim 1, wherein said dielectric comprises a solid.

9. The artificial dielectric of claim 8, wherein said dielectric comprises polyethylene.

10. The artificial dielectric of claim 8, wherein said dielectric comprises polypropylene.

11. The artificial dielectric of claim 8, wherein said dielectric comprises alumina.

12. The artificial dielectric of claim 8, wherein said dielectric comprises magnesium oxide.

13. The artificial dielectric of claim 1, wherein said dielectric comprises an organic or inorganic matrix.

14. The artificial dielectric of claim 1, wherein said dielectric comprises a thin film.

15. The artificial dielectric of claim 1, wherein a dielectric constant of the artificial dielectric is a function of an applied electric field.

16. The artificial dielectric of claim 1, wherein a dielectric constant of the artificial dielectric is a function of the density of the nanostructures.

17. The artificial dielectric of claim 1, wherein a dielectric constant of the artificial dielectric is a function of the conductivity of the nanostructures.

18. The artificial dielectric of claim 1, wherein a dielectric constant of the artificial dielectric is a function of the length, shape or aspect ratio of the nanostructures.

19. The artificial dielectric of claim 1, wherein a dielectric constant of the artificial dielectric is a function of the orientation of the nanostructures.

20. A capacitor, comprising:

a first capacitor plate,

a second capacitor plate separated from said first capacitor plate,

an artificial dielectric located between said first and second capacitor plates, wherein said artificial dielectric includes

a dielectric; and

a plurality of nanostructures embedded within said dielectric.

21. The capacitor of claim 20, wherein said nanostructures have at least one component which is approximately perpendicular to said first and second capacitor plates.

22. A thin film electronic device comprising an artificial dielectric, wherein said artificial dielectric includes a dielectric and nanowires embedded within said dielectric.

23. A thin film transistor, comprising:

a substrate;

a gate electrode;

an artificial dielectric including a dielectric film and a plurality of nanostructures embedded within said dielectric film;

a semiconducting film;

a source electrode; and

a drain electrode.

24. The thin film transistor of claim 23, wherein said substrate comprises polyethylenenaphthalate.

25. The thin film transistor of claim 23, wherein said gate electrode, source electrode and drain electrode comprise polyaniline.

26. The thin film transistor of claim 23, wherein said dielectric film comprises polyimide.

27. The thin film transistor of claim 23, wherein said nanostructures are doped.

28. The thin film transistor of claim 23, wherein said nanostructures comprise nanowires that are silicon and said dopant comprises arsenic, phosphorus or boron.

29. The thin film transistor of claim 28, wherein said nanowires are semiconductors.

30. A material for absorbing electromagnetic waves, comprising

a plurality of layers of an artificial dielectric including a dielectric material and a plurality of embedded nanostructures; and

a metal substrate to support said plurality of layers of an artificial dielectric.

31. A vehicle comprising:

a coating of a radar absorbing material (RAM) over a portion of said vehicle; and

a controllable artificial dielectric material that includes nanostructures that covers a portion of said vehicle, wherein a reflectivity of said controllable artificial dielectric material is adjusted by application of an electric field to said artificial dielectric.

32. The vehicle of claim 31, wherein said vehicle is an aircraft or ship.

33. A method to create an electronic device having an artificial dielectric using nanowires, comprising:

(a) mixing a plurality of nanostructures into a polymer to create the artificial dielectric using said nanostructures;

(b) extruding the artificial dielectric using nanostructures created in step (a) into a thin film;

(c) coating a top and a bottom of said thin film with a metal; and

(d) patterning said metal coating based on the type of electronic device.

34. A method to create an electronic device having an artificial dielectric using nanowires on a circuit board, comprising:

(a) mixing a plurality of nanowires into a polymer to create the artificial dielectric using nanowires;

(b) extruding the artificial dielectric using nanowires created in step (a) into a thin film;

(c) applying the thin film to selected areas of the circuit board where the electronic device is desired; and

(d) providing a ground plane above the selected areas where the thin film has been applied.

35. A method of forming an artificial dielectric, comprising:

(a) forming a dielectric; and

(b) adding nanostructures to the dielectric.

36. The method of claim 35, further comprising adjusting a dielectric constant of the artificial dielectric by varying the number of nanostructures.

37. The method of claim 35, further comprising adjusting a dielectric constant of the artificial dielectric by doping the nanostructures.

38. The method of claim 35, further comprising adjusting a dielectric constant or frequency response of the artificial dielectric by varying the size, shape, or length of the nanostructures.

39. The method claim 35, further comprising adjusting a dielectric constant of the artificial dielectric by varying the orientation of the nanostructures.

40. The method claim 35, further comprising forming dielectric with the nanostructures into a thin film.

41. The method of claim 40, further comprising applying the thin film to a substrate.