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TERAHERTZ RESONATOR

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Schubert et al.

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(54) **TERAHERTZ RESONATOR**

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U.S.C. 154(b) by 513 days.

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20, 2009.

(51) **Int. Cl.**
G01T 1/17 (2006.01)
G01J 5/08 (2006.01)

(52) **U.S. Cl.**
USPC **250/336.1**; 250/338.1

(58) **Field of Classification Search**
USPC 250/336.1, 338.1; 977/720, 722,
977/766, 810; 398/116
See application file for complete search history.

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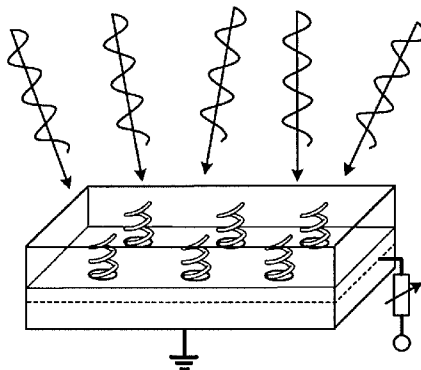
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(57) **ABSTRACT**

A tunable terahertz resonator includes a semiconductor sub-
strate and a metal layer contacting a surface of the semicon-
ductor substrate. A depletion layer is formed in the semicon-
ductor substrate near an interface between the metal layer and
the semiconductor substrate. A chiral nanostructure is
coupled to the substrate or the metal layer, the chiral nano-
structure including a conducting or semiconducting material
and having an inductance. A bias circuit applies a bias voltage
across the metal layer and the semiconductor substrate to
control a capacitance of a tunable capacitor that includes the
depletion layer. The chiral nanostructure and the tunable
capacitor form a tunable resonant circuit. The tunable tera-
hertz resonator can be used in a terahertz radiation emitter or
receiver.

25 Claims, 5 Drawing Sheets



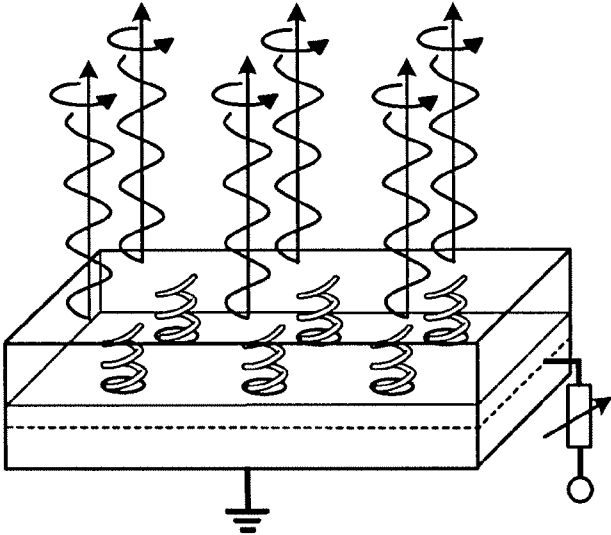


FIG. 1A

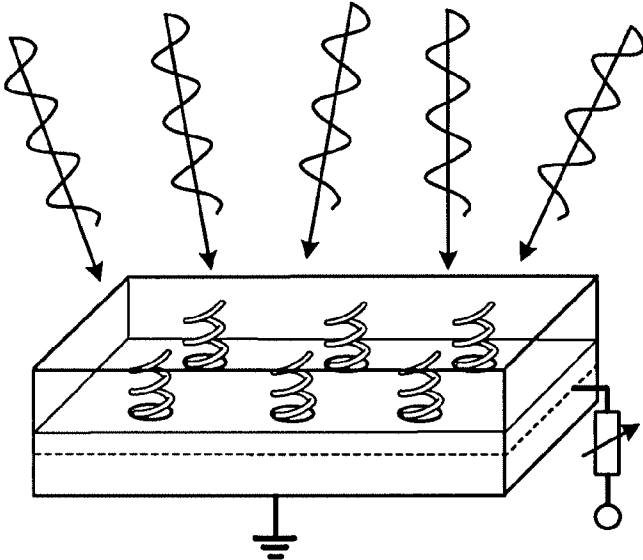
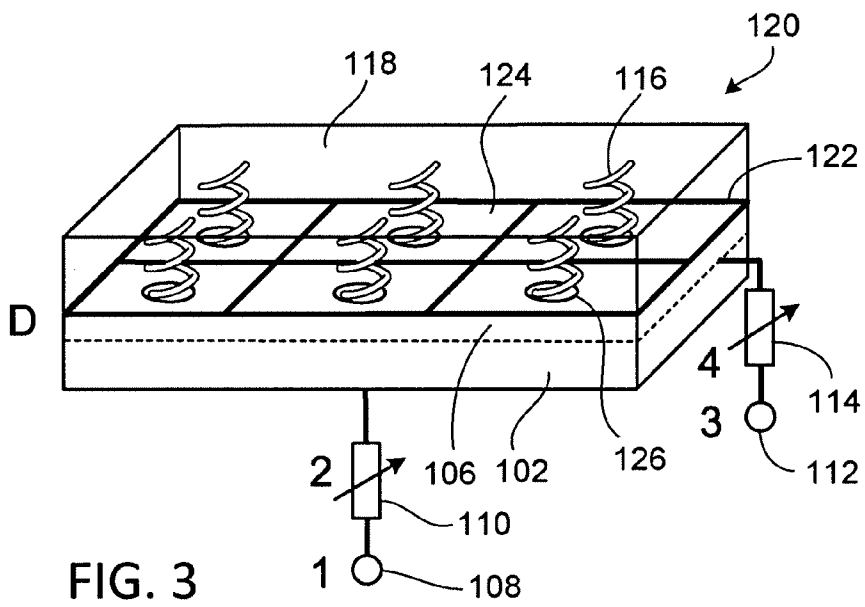
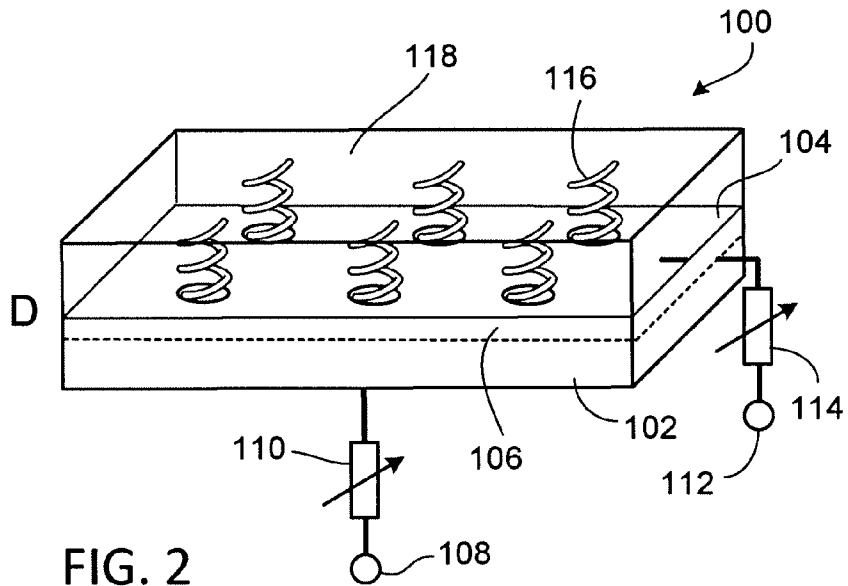


FIG. 1B



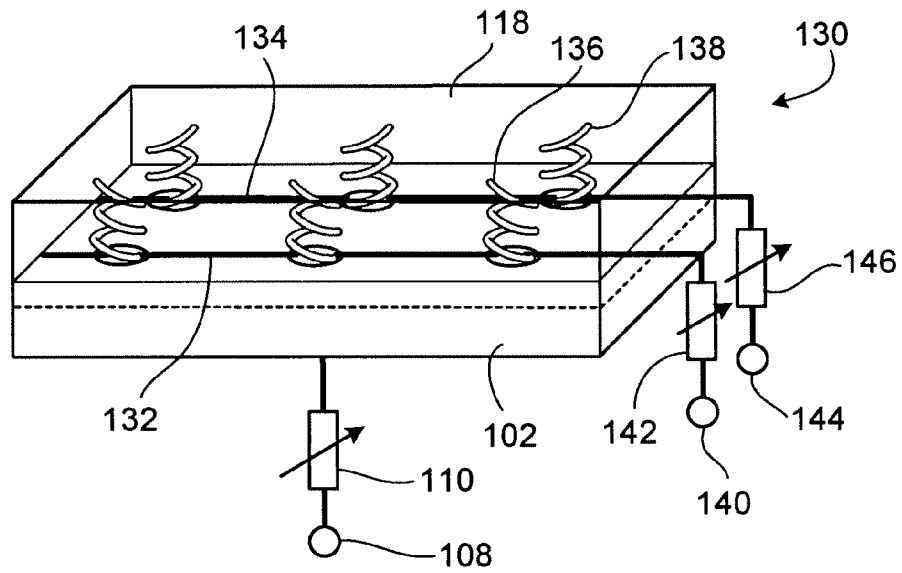


FIG. 4

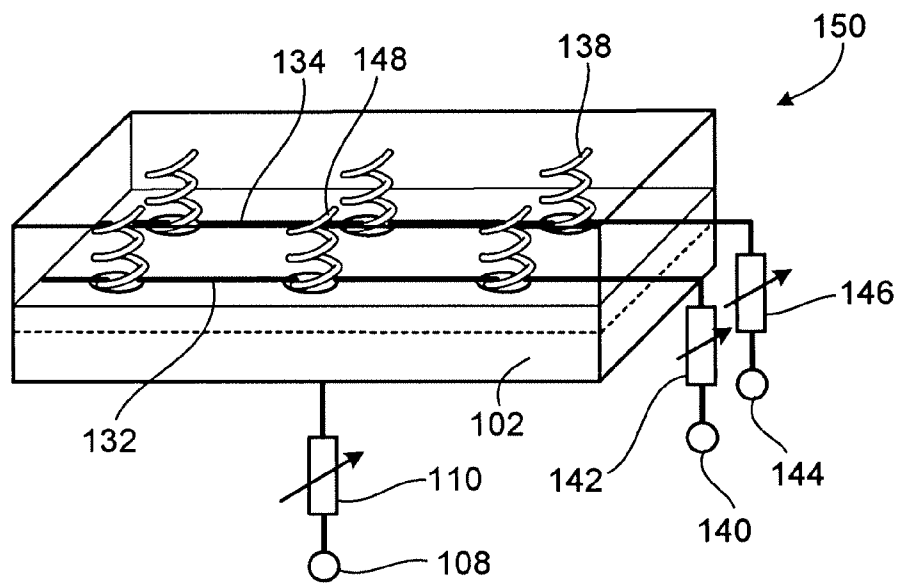


FIG. 5

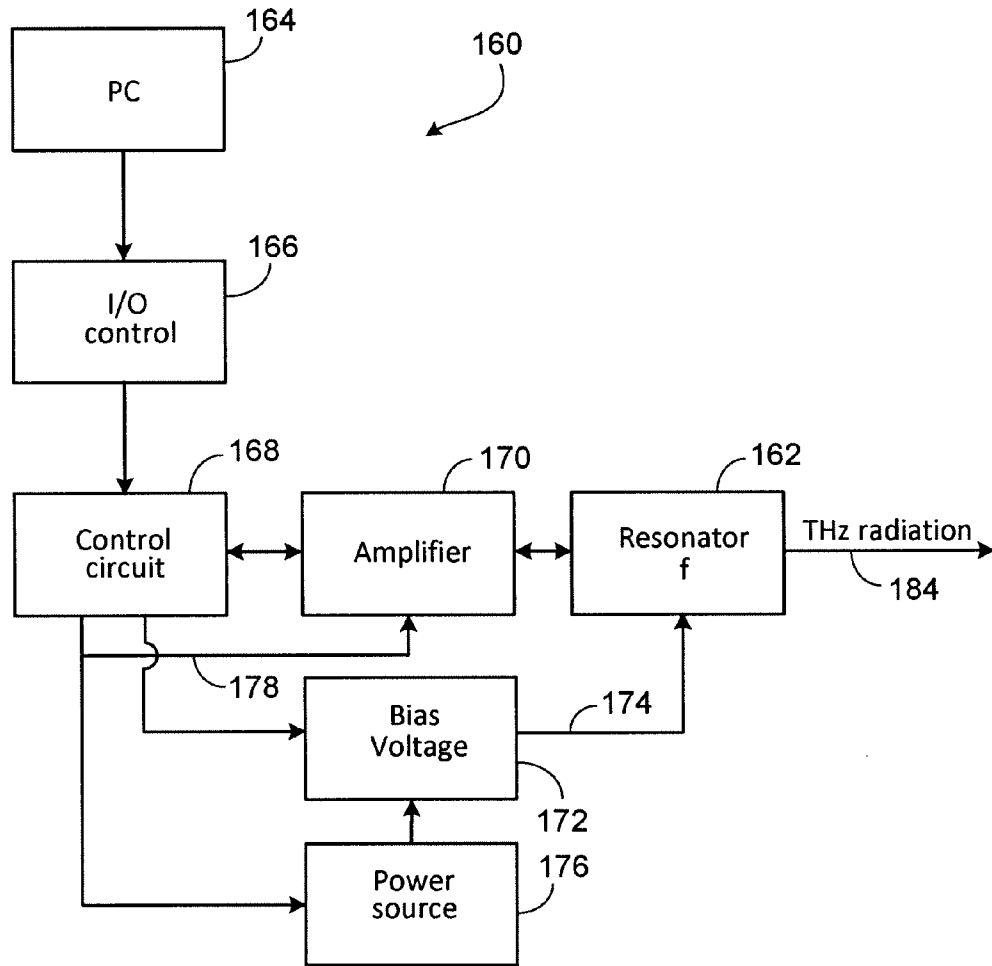


FIG. 6

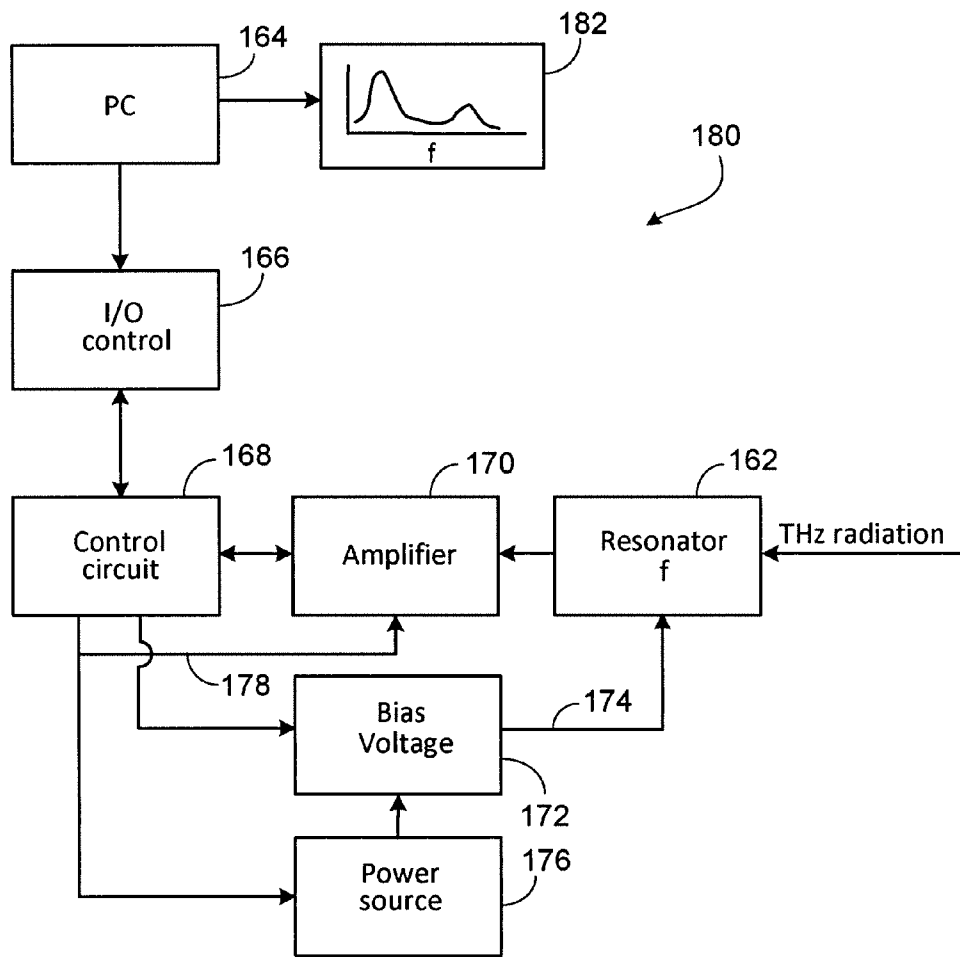


FIG. 7

TERAHERTZ RESONATOR

CROSS-REFERENCE TO RELATED
APPLICATIONS

This application claims priority to U.S. Provisional Application Ser. No. 61/216,659, filed May 20, 2009. The above application is incorporated herein by reference in its entirety.

STATEMENT AS TO FEDERALLY SPONSORED
RESEARCH

This invention was made with government support under Grant No. 0824920 awarded by NSF. The government has certain rights in the invention.

TECHNICAL FIELD

This subject matter is generally related to terahertz resonators.

BACKGROUND

Terahertz radiation (having a frequency from about 0.3 THz to about 30 THz) has many useful properties. For example, it can penetrate many materials, such as plastics, textile, paper, and wood, but is absorbed in metals. Terahertz radiation imaging and sensing can be useful in, for example, medical imaging, security and surveillance, materials characterization, and data communication. Security systems that use terahertz imaging can detect hidden objects under clothes. Terahertz radiation may interact with certain molecules to cause absorption of the radiation, providing spectroscopic fingerprints for the molecules. Terahertz radiation may be used to detect skin cancers not visible to the naked eye. Terahertz radiation can also produce useful information about properties, such as bound and unbound charge carrier modes, of solid state materials.

SUMMARY

In general, in one aspect, an apparatus includes a tunable terahertz resonator and a bias circuit. The tunable terahertz resonator includes a semiconductor substrate; a metal layer contacting a surface of the semiconductor substrate, a depletion layer being formed in the semiconductor substrate near an interface between the metal layer and the semiconductor substrate; and a chiral nanostructure coupled to the substrate or the metal layer, the chiral nanostructure including a conducting or semiconducting material and having an inductance. The bias circuit applies a bias voltage across the metal layer and the semiconductor substrate to control a capacitance of a tunable capacitor that includes the depletion layer, the chiral nanostructure and the tunable capacitor forming a tunable resonant circuit.

Implementations of the apparatus may include one or more of the following features. A control circuit can be provided to adjust a resonant frequency of the resonant circuit by controlling the bias circuit to adjust the capacitance of the depletion layer such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz. The control circuit can sweep the bias voltage from a first voltage to a second voltage to cause the resonant frequency of the resonant circuit to sweep from a first frequency to a second frequency. A terahertz transmitter can include the terahertz resonator, and a power source to provide electric power to the tunable terahertz resonator, wherein the tunable terahertz resonator converts the

electric power into terahertz electromagnetic radiation that is emitted from the terahertz transmitter. A terahertz detector can include the terahertz resonator, and an amplifier to amplify terahertz radiation received by the tunable terahertz resonator. The chiral nanostructure can include a nanocoil. The bias circuit can provide pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.

In general, in another aspect, an apparatus includes a tunable terahertz resonator and a bias circuit. The tunable terahertz resonator includes a semiconductor substrate; a plurality of metal regions on the semiconductor substrate, a depletion layer being formed in the semiconductor substrate near an interface between each metal region and the semiconductor substrate, each metal region and corresponding depletion layer and corresponding portion of the semiconductor substrate forming a tunable capacitor; and a plurality of chiral nanostructures each coupled to one of the metal regions, each chiral nanostructure including a conducting or semiconducting material and having an inductance, each chiral nanostructure and the corresponding tunable capacitor forming a tunable terahertz resonant circuit. The bias circuit provides a bias voltage across each metal region and the semiconductor substrate to control a capacitance of the tunable capacitor to control a resonant frequency of the resonant circuit; wherein at least two of the plurality of tunable terahertz resonant circuits can be controlled independently of each other.

Implementations of the apparatus may include one or more of the following features. The chiral nanostructures can include right-handed chiral nanostructures and left-handed chiral nanostructures. The terahertz resonator can be operable in a first mode and a second mode. In the first mode, the number of activated resonant circuits having the right-handed chiral nanostructures is greater than the number of activated resonant circuits having the left-handed chiral nanostructures. In the second mode, the number of activated resonant circuits having the left-handed chiral nanostructures is greater than the number of activated resonant circuits having the right-handed chiral nanostructures. The control circuit can control the bias voltages applied to the at least two tunable terahertz resonant circuits that can be controlled independently of each other to independently adjust the resonant frequencies of the at least two resonant circuits. The bias circuit can provide pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.

In general, in another aspect, an apparatus includes a tunable terahertz resonator and a bias circuit. The tunable terahertz resonator includes a tunable capacitor; and a three-dimensional nanostructure coupled to the tunable capacitor, the nanostructure having an inductance, the nanostructure and the tunable capacitor forming a resonant circuit. The bias circuit applies a bias voltage across the tunable capacitor, the bias voltage controlling a capacitance of the tunable capacitor such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz.

Implementations of the apparatus may include one or more of the following features. The three-dimensional nanostructure can include a chiral nanostructure. The tunable capacitor can include a depletion region in a semiconductor substrate. The nanostructure and the tunable capacitor can be aligned along a first direction, the nanostructure having a footprint that is less than 10^{-8} cm² on a surface perpendicular to the first direction. The bias circuit can provide pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.

In general, in another aspect, a method includes applying a bias voltage across a metal layer and a semiconductor sub-

strate to control a thickness of a depletion region near an interface between the metal layer and the semiconductor substrate, the depletion region having a capacitance that is dependent on the thickness of the depletion region, the depletion region being electrically coupled to a chiral nanostructure to form a resonant circuit, the chiral nanostructure being made of a conducting or semiconducting material and having an inductance; and controlling the bias voltage to adjust a resonant frequency of the resonant circuit.

Implementations of the method may include one or more of the following features. The nanostructure can have dimensions selected to cause the nanostructure to have a predetermined inductance such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz when the bias voltage is within a predetermined range. The method can include receiving a terahertz radiation at the resonant circuit, and processing the received terahertz radiation. The method can include sweeping the bias voltage from a first voltage level to a second voltage level to cause the resonant frequency of the resonant circuit to sweep from a first frequency to a second frequency, and performing spectroscopy on the received terahertz radiation. The method can include providing electric power to the resonant circuit and causing the resonant circuit to emit terahertz radiation. The method can include providing pulse voltage signals to the resonant circuit to initiate oscillation of the resonant circuit.

In general, in another aspect, a method of operating a terahertz resonator includes applying at least one bias voltage to a plurality of tunable terahertz resonant circuits formed on a semiconductor substrate, each resonant circuit including a tunable capacitor electrically coupled to an inductor that includes a chiral nanostructure, the at least one bias voltage being applied to the tunable capacitors to control capacitances of the tunable capacitors, the chiral nanostructure having dimensions selected to cause the chiral nanostructure to have a predetermined inductance such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz when the bias voltage is within a predetermined range; and independently controlling the bias voltages applied to at least two of the resonant circuits to independently adjust the resonant frequencies of the at least two resonant circuits.

Implementations may include one or more of the following features. The method can include providing signals to the at least two independently controlled resonant circuits and emitting terahertz radiation from the at least two independently controlled resonant circuits using at least two different terahertz frequencies. The nanostructures can include right-handed chiral nanostructures and left-handed chiral nanostructures that are individually selectable. The method can include operating the resonant circuits in a first mode by activating at least some resonant circuits having the right-handed chiral nanostructures and de-activating at least some resonant structures having the left-handed chiral nanostructures, and operating the resonant circuits in a second mode by activating at least some resonant circuits having the left-handed chiral nanostructures and de-activating at least some resonant structures having the right-handed chiral nanostructures. The method can include providing pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.

In general, in another aspect, a method of fabricating a resonant circuit includes forming a metal layer on a semiconductor substrate in which a depletion layer is formed near an interface between the metal layer and the semiconductor substrate, the depletion layer having a capacitance; and forming a nanostructure on the metal layer or the semiconductor substrate, the nanostructure being made of a conducting or semi-

conducting material and having dimensions selected to cause the nanostructure to have a predetermined inductance, the nanostructure and the depletion layer forming a resonant circuit.

Implementations may include one or more of the following features. The resonant circuit can have a resonant frequency in a range between 0.3 to 30 THz when the bias voltage is within a predetermined range. Forming the nanostructure can include using glancing angle deposition to deposit the conducting or semiconducting material to form the nanostructure.

These features allow a user to generate or detect terahertz radiation using devices that are low cost and robust.

DESCRIPTION OF DRAWINGS

FIG. 1A is a diagram of an example terahertz resonator emitting terahertz radiation.

FIG. 1B is a diagram of an example terahertz resonator receiving terahertz radiation.

FIGS. 2 to 5 are diagrams of example terahertz resonators.

FIG. 6 is a block diagram of a terahertz transmitter.

FIG. 7 is a block diagram of a terahertz receiver.

DETAILED DESCRIPTION

This disclosure relates to a terahertz resonator that has a nanostructure coupled to a tunable capacitor to form a resonant circuit. The nanostructure has at least one dimension in the nanometer length scale. The nanostructure can be, e.g., a chiral nanostructure such as a nanocoil. The tunable capacitor can be provided by forming a metal layer on a semiconductor substrate to form a Schottky-barrier capacitor whose capacitance depends on the thickness of the Schottky-barrier induced depletion zone. The capacitance is tunable by controlling a bias voltage applied across the metal layer and the semiconductor substrate. The configurations for the nanostructure and the tunable capacitor, and the bias voltage applied to the tunable capacitor, are selected such that the resonant circuit has a resonant frequency in the terahertz range from 0.3 to 30 THz.

Referring to FIG. 1A, a terahertz resonator can be part of a transmitter that emits terahertz electromagnetic radiation. In this example, the terahertz resonator includes chiral nanostructures that emit circularly polarized electromagnetic radiation. Referring to FIG. 1B, a terahertz resonator can be part of a detector that detects terahertz electromagnetic radiation. The incoming radiation can be unpolarized, or polarized in any way, such as linear, circular, or elliptical.

Referring to FIG. 2, in some implementations, a terahertz resonator **100** includes a p-type doped silicon substrate **102** and a metal layer **104** contacting a surface of the substrate **102**. A Schottky-barrier induced depletion layer **106** is formed in the substrate **102** in a region near the surface facing the metal layer **104**. The depletion layer **106** has a capacitance. Nanocoils **116**, made of metals such as copper (Cu), aluminum (Al), or titanium (Ti), can be grown on the metal layer **104** by, e.g., glancing angle deposition (GLAD). The nanocoil **116** each has an inductance. The nanocoil **116** and the depletion layer **106** form an L-C resonant circuit having a resonant frequency that depends on the inductance of the nanocoil **116** and the capacitance of the depletion layer **106**.

An insulating layer **118** can be applied over the nanocoils **116** and filled into the pore volume of the nanocoil and the space between turns of the nanocoil. The insulating layer **118** insulates the turns of the coil and serves as a protective layer. For example, the insulating layer **118** can be made of a dielec-

tric polymer. Polyvinyl phenol (PVP) can be cross-linked with poly (melamine-co-formaldehyde) (PMF), and both the prepolymer and the cross-linking agent can be solved in propylene glycol methyl ether acetate (PGMEA). Spin coating can be used to evenly distribute the polymer on top of the nanocoils **116**. Subsequent cross-linking can be achieved by thermal annealing in a vacuum oven.

A first bias voltage is applied to the substrate **102** using a voltage source **108** and an adjustable voltage control **110**, which can adjust the bias voltage applied to the substrate **102**. A second bias voltage is applied to the metal layer **104** and the nanocoils **116** using a voltage source **112** and an adjustable voltage control **114**, which can adjust the bias voltage applied to the metal layer **114** and the nanocoils **116**. The bias voltage across the metal layer **104** and the substrate **102** (which is equal to the bias voltage applied to the metal layer **104** minus the bias voltage applied to the substrate **102**) affects the thickness of the depletion layer **106**, which in turn affects the capacitance of the depletion layer **106**. By adjusting the voltage control **110** and the voltage control **114** to change the bias voltage applied across the substrate **102** and the metal layer **104**, the resonant frequency of the resonator **100** can be adjusted.

Referring to FIG. **3**, in some implementations, instead of using a continuous metal layer **104** as in the example of FIG. **2**, a metal grid **122** can be used. The metal grid **122** has openings that expose the surface **124** of the silicon substrate **102**. In this example, nanocoils **116** are grown on the surface of the substrate **102** by, e.g., glancing angle deposition (GLAD). The native oxide layer on the silicon substrate **102** is removed using, e.g., wet chemical etching or low-energy ion beam etching, prior to forming the nanocoils **116** on the substrate **102**. Similar to the example in FIG. **2**, the nanocoils **116** in the example of FIG. **3** can be covered by a layer of dielectric polymer **118**.

In this example, a first bias voltage is applied to the substrate **102** using a voltage source **108** and an adjustable voltage control **110**. A second bias voltage is applied to the metal grid **122** (but not the nanocoils **116**) using a voltage source **112** and an adjustable voltage control **114**, which can adjust the bias voltage applied to the metal grid **122**. The resonant frequency of the terahertz resonator **120** can be adjusted by adjusting the bias voltage across the metal grid **122** and the substrate **102**.

A number of terahertz resonators **120** having different configurations were tested using simulation. Table 1 below shows the dimension of several examples of the terahertz resonator **120**. In the table, A represents the area of the nanocoil footprint, l represents the length of the nanocoil **116**, N represents the number of turns of the nanocoil **116**, d represents the thickness of the depletion layer **106**, L represents the inductance of the nanocoil **116**, C represents the capacitance of the depletion layer **106**, and ν represents the resonant frequency.

TABLE 1

A (cm ²)	l (μ m)	N	d (nm)	L (Vs/A)	C (As/V)	ν (THz)
4×10^{-10}	2.5	10	100	2×10^{-12}	3.5×10^{-18}	29
4×10^{-10}	2.5	10	10	8×10^{-12}	3.5×10^{-17}	9
4×10^{-10}	2.5	10	5	8×10^{-12}	7.0×10^{-17}	6.7
4×10^{-10}	1.25	5	10	1×10^{-12}	3.5×10^{-17}	27
4×10^{-10}	1.25	5	5	1×10^{-12}	7.0×10^{-17}	19

Referring to FIG. **4**, in some implementations, the metal layer can be configured to allow individual control of groups of resonators. For example, a terahertz resonator **130** includes a first metal strip **132** and a second metal strip **134** both

formed on a surface of a p-type silicon substrate **102**. Left-handed nanocoils **136** are grown above the metal strip **132**, and right-handed nanocoils **138** are grown above the metal strip **134**. Similar to the example in FIG. **2**, the nanocoils **136** and **138** in the example of FIG. **4** can be covered by a layer of dielectric polymer **118**.

A bias voltage is applied to the substrate **102** using a voltage source **108** and an adjustable voltage control **110**. A bias voltage is applied to the metal strip **132** and the nanocoils **136** using a voltage source **140** and an adjustable voltage control **142**. A bias voltage is applied to the metal strip **134** and the nanocoils **138** using a voltage source **144** and an adjustable voltage control **146**. By controlling the adjustable voltage controls **142** and **146**, the left-handed nanocoils **132** and the right-handed nanocoils **134** can be independently activated or selected.

For example, the left-handed nanocoils **132** can be activated by applying a bias voltage to the metal strip **132** to cause the resonant circuits formed by the nanocoils **132** and the depletion layer beneath the metal strip **132** to have a resonant frequency in the terahertz range 0.3 to 30 THz. The right-handed nanocoils **134** can be de-activated by either not applying a bias voltage to the metal strip **134** or applying a bias voltage to the metal strip **134** such that no oscillation occurs for the resonant circuits that includes the nanocoils **134**.

When only the left-handed nanocoils **132** are activated, the terahertz resonator **130** can be used to transmit or receive left-handed circularly polarized terahertz electromagnetic waves. When only the right-handed nanocoils **134** are activated, the terahertz resonator **130** can be used to transmit or receive right-handed circularly polarized terahertz electromagnetic waves. When both left-handed and right-handed nanocoils **132** and **134** are activated, the terahertz resonator **130** can be used to transmit or receive both left-handed and right-handed circularly polarized terahertz electromagnetic waves.

In some implementations, the relative percentages of the activated left-handed nanocoils versus activated right-handed nanocoils can be varied. By varying the relative percentages of left-handed and right-handed nanostructures, the terahertz resonator **130** can become preferentially selective for either one of the polarization, and act as a polarizer.

In some implementations, the terahertz resonator **130** can become preferentially selective for either one of the polarization by electronically emphasizing the signals received from the respective nanocoils during terahertz detection, or by selectively stimulating (amplitude) the respective nanocoils during terahertz emission.

The resonator structure **130** can be configured to detect or emit either left or right handed elliptical, circular and linear polarization. If as described above the resonator structure **130** is asymmetrically amplified (at the same bias voltage for the same resonant frequency), or asymmetrically loaded with nanostructures, the resulting transmittance or acceptance characteristic can be chosen to match that of either left or right-handed elliptically polarized light.

Furthermore, if a phase shift is induced by the amplifier such that the transmitted and detected signals for both left and right handed resonator structures are delayed between zero and 360 degrees, and if both left and right handed amplitudes are the same, linear polarized light will be preferentially detected, or emitted.

Referring to FIG. **5**, in some implementations, a terahertz transmitter **150** having two or more groups of nanocoils (e.g., **138** and **148**) can form a phased-array transmitter. The nanocoils of different groups can have the same configuration (e.g., can be all right-handed or left-handed) but receive sig-

nals from signal sources (not shown in the figure) having different phases. The interferences among the terahertz electromagnetic waves emitted by the different groups of nanocoils cause the envelope of the terahertz radiation to have particular shapes. For example, the signals sent to the groups of nanocoils (e.g., **138** and **148**) can be configured such that a narrow terahertz beam is emitted from the terahertz resonator **150**. The signals sent to the groups of nanocoils can be configured such that the beam direction changes over time.

The bias voltages applied to different groups of resonant circuits can be different such that different groups of resonant circuits have different resonant frequencies. For example, the adjustable voltage control **142** and the adjustable voltage control **146** can be independently controlled to provide different bias voltages to the metal strips **132** and **134**. This allows the resonator **150** to emit or detect terahertz radiation at multiple frequencies at the same time.

FIG. **5** only shows two metal strips and two groups of nanocoils. Because the nanocoils have very small dimensions, the terahertz resonator **150** can have many (e.g., hundreds or more) groups of nanocoils that can be individually controlled. When operating as a phased-array transmitter, the groups of nanocoils can generate highly directional terahertz electromagnetic waves. In a phased-array transmitter, individual resonant circuits are operated with a phase delay relative to one another so as to produce a highly directional radiation emitting from the surface of the array.

Similarly, when operating as a phased-array receiver, the groups of nanocoils can function as a highly directional antenna that is particularly sensitive to detecting terahertz electromagnetic waves propagating along a certain direction relative to the surface of the terahertz resonator. In a phased-array receiver, individual resonant circuits are operated with a phase delay relative to one another so as to produce a highly directional sensitivity to the incident radiation.

Referring to FIG. **6**, in some implementations, a terahertz transmitter **160** includes a terahertz resonator **162** having a resonant frequency in the terahertz range 0.3 to 30 THz. The resonator **162** can be similar to, e.g., the resonator **100** (FIG. **2**), **120** (FIG. **3**), **130** (FIG. **4**), or **150** (FIG. **5**). A computer **164**, such as a personal computer, provides a user interface to allow a user to conveniently control the operations of the terahertz transmitter **160**. The computer **164** controls a control circuit **168** through an input/output control interface **166**. The control circuit **168** sends signals (e.g., pulse signals) to an amplifier **170**, which amplifies the signals and sends the output to the resonator **162**. The control circuit **168** may control the gain of the amplifier using a control signal line **178**. The control circuit **168** controls a bias voltage generator **172** that provides a bias voltage **174** to the resonator **162** to control the resonant frequency of the resonator **162**. The control circuit **168** also controls a power source **176**, which provides power to the bias voltage generator **172**.

During startup of the terahertz transmitter **160**, the control circuit **168** causes the bias voltage generator **172** to provide a DC bias voltage, and the amplifier **170** to provide short-pulse voltage sequences so as to bring the resonator **162** into oscillation. The output of the resonator **162** is terahertz radiation **184**. The terahertz electromagnetic waves transmitted by the terahertz transmitter **160** can be modulated to carry information, such as voice or data. In some examples, the amplifier **170** amplifies a small voltage modulation from the control circuit **168** and provides the amplified voltage modulation to the resonator **162**.

The computer **164** can control the bias voltage to sweep from a first voltage level to a second voltage level to cause the resonant frequency of the resonator **162** to sweep from a first

frequency to a second frequency. This causes the transmitter **160** to emit terahertz radiation having a frequency that sweeps from the first frequency to the second frequency. This is useful when performing spectroscopy. The terahertz radiation can be directed to a compound or object, and the reflected or transmitted radiation can be analyzed to determine the properties of the object.

The computer **164** may provide a user interface for interacting with a user, including receiving commands from the user indicating the desired frequency or frequency range of the terahertz radiation **184**. The computer **164** may include storage to store instruction code that is executed by the computer to perform the various tasks described here.

Referring to FIG. **7**, in some implementations, a terahertz detector **180** includes a terahertz resonator **162** having a resonant frequency in the terahertz range 0.3 to 30 THz. A computer **164** provides a user interface to allow a user to conveniently control the operations of the terahertz detector **180**. The computer **164** controls a control circuit **168** through an input/output control interface **166**. The control circuit **168** may control the gain of an amplifier **170** using a control signal line **178**. The control circuit **168** controls a bias voltage generator **172** that provides a bias voltage **174** to control the resonant frequency of the resonator **162**. A power source **176** provides power to the bias voltage generator **172**.

During startup of the terahertz detector **180**, the control circuit **168** causes the bias voltage generator **172** to provide a DC bias voltage. When the terahertz detector **180** receives terahertz electromagnetic waves having a frequency that matches the resonant frequency of the resonator **162**, the amplitudes of the resonant oscillations will augment a small bias voltage variation, according to the strength of the received signal. The small variations in the bias voltage (representing the received signal) are differentiated from the supplied bias voltage and amplified by the amplifier **170**, and processed via the control circuit **168**, the input/output control unit **166**, and the computer **164**.

The computer **164** can control the bias voltage to sweep from a first voltage level to a second voltage level to cause the resonant frequency of the resonator **162** to sweep from a first frequency to a second frequency. The computer **164** records the signal strength of the received signals at various frequencies and performs a spectroscopy of the incident radiation. A spectral analysis of the incident radiation can be displayed as a graph **182**.

The computer **164** may provide a user interface for interacting with a user, including receiving commands from the user and displaying results of spectral analyses. The computer **164** may include storage to store instruction code that is executed by the computer to perform the various tasks described here.

In some implementations, the terahertz resonator can have an array of rows and columns of nanostructures that can be individually accessed through row and column control lines. The terahertz resonator can be used in a terahertz display or projector for displaying or projecting two-dimensional images in the terahertz spectrum. The terahertz resonator can also be used in a terahertz sensor for sensing two-dimensional images in the terahertz spectrum.

For example, an active switch (such as a transistor) can be provided at each intersection of the row and column control lines. Each intersection of the row and column control lines corresponds to a "pixel" in the terahertz display or sensor. A row of resonant circuits can be activated, and the column lines can be used to send different signals to different resonant circuits or receive signals from the resonant circuits. Different

rows of resonant circuits can be sequentially activated to generate different row portions of the transmitted or received image.

In some implementations, the terahertz resonator can have an array of rows and columns of groups of nanostructures, in which each group of nanostructure can be individually accessed. For example, each active switch can be associated with two or more nanocoils. This may increase the sensitivity of each pixel in the sensor and reduce noise in the detected image.

As described above, the terahertz transmitter **160** can be used as polarization state generator (PSG), and the terahertz detector **180** can be used as polarization state detector (PSD). A polarization state generator includes a light source and a set of arbitrarily configurable polarizer components to achieve all polarization characterized as linear, elliptical, or circular, covering both handedness, and all 360 degree spatial preference directions for linear and elliptical polarizations, and all ellipticities. A polarization state detector includes a light detector and a set of arbitrarily configurable polarizer components to achieve all polarization characterized as linear, elliptical, circular, covering both handedness, and all 360 degree spatial preference directions for linear and elliptical polarizations, and all ellipticities. An ellipsometer includes a polarization-tunable PSG device and a polarization-tunable PSD device. Therefore, a combination of the terahertz transmitter **160** and the terahertz detector **180** can be used to operate an ellipsometer system, with the terahertz transmitter emitting radiation that is projected on a sample, and the terahertz receiver detecting radiation reflected from or transmitted through the sample. Because the terahertz transmitter **160** and the terahertz detector **180** can be tuned spectrally, this ellipsometer can be operated as a spectral ellipsometer in the terahertz spectral region.

An advantage of the terahertz resonators described above is that they can be small and low cost. Although nanocoils were used in the examples described above, other nanostructures, either chiral or achiral, can also be used. For example, the resonators can include achiral nanostructures, such as vertical posts and slanted posts.

In some implementations, the nanostructures can be generated in a self-organized growth process by using glancing angle deposition (GLAD) accompanied with a controlled substrate motion. For example, the substrate **102** can be rotated continuously to form nanocoils. Sculptured thin films with tailored designs can be grown from a broad variety of different materials (semiconductors and metals) by using physical vapor deposition methods. Glancing angle deposition is a method to generate three-dimensional (3D) chiral nanostructures from a concurrent growth mechanism due to geometrical shadowing in combination with kinetic limitation for surface adatoms. This technique uses a particle flux reaching the substrate under an oblique angle of incidence (for example, greater than 80°). These conditions support a columnar growth, and the instantaneous change of the growth direction due to a simple variation of the incident vapor flux (by substrate rotation) allows for the fabrication of 3D nanostructures with manifold morphologies.

Some description of the principles of sculptured thin film preparation by glancing angle deposition can be found in "Uniaxial magnetic anisotropy in cobalt films induced by oblique deposition of an ultrathin cobalt underlayer," by M. T. Umlor, *Appl. Phys. Lett.* 87, 082505 (2005).

Glancing angle deposition sculptured thin film can be prepared using, for example, semiconducting materials, such as silicon. Metal (for example, Co, Cu, W, Al) nanorods, whiskers, and nanopillars can also be grown using glancing angle

deposition. Sculptured thin films from metal with morphologies that render chiral structures can also be grown using glancing angle deposition.

A calibration of the resonators may be performed such that the resonant frequencies are measured for different bias voltages. The calibration data may be stored in the storage of the computer **164**. When the resonators are used to generate or detect terahertz radiation of a particular frequency, the calibration data are retrieved and the resonators are biased to a corresponding voltage.

Although some examples have been discussed above, other implementations and applications are also within the scope of the following claims. For example, the nanostructures can have shapes and sizes that are different from those described above. The nanostructures can be, for example, a three-dimensional object with dimensions in the nanometer length scale, with one spatial extension longer than the two remaining spatial extensions, and having kinks and curvatures along the long extension so as to form, e.g., straight wires, zigzags, staircases, zigzagged or continuous coils. The metal layer and nanostructures can be made from materials that are different from those described above. The substrate **102** can be either n-type or p-type, and can be made of any other type of semiconductor material that is capable of forming a metal Schottky barrier induced depletion layer.

The various examples and features described above related to data processing can be implemented in digital electronic circuitry, or in computer hardware, firmware, software, or in combinations of them. The features can be implemented in a computer program product tangibly embodied in an information carrier, e.g., in a machine-readable storage device or in a propagated signal, for execution by a programmable processor; and method steps can be performed by a programmable processor executing a program of instructions to perform functions of the described implementations by operating on input data and generating output.

The described features can be implemented advantageously in one or more computer programs that are executable on a programmable system including at least one programmable processor coupled to receive data and instructions from, and to transmit data and instructions to, a data storage system, at least one input device, and at least one output device. A computer program is a set of instructions that can be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program can be written in any form of programming language (e.g., Objective-C, Java), including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment.

Suitable processors for the execution of a program of instructions include, by way of example, both general and special purpose microprocessors, and the sole processor or one of multiple processors or cores, of any kind of computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. The essential elements of a computer are a processor for executing instructions and one or more memories for storing instructions and data. Generally, a computer will also include, or be operatively coupled to communicate with, one or more mass storage devices for storing data files; such devices include magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and optical disks. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM, EEPROM, and flash

memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

What is claimed is:

1. An apparatus comprising:
 - a tunable terahertz resonator comprising:
 - a semiconductor substrate;
 - a metal layer contacting a surface of the semiconductor substrate, a depletion layer being formed in the semiconductor substrate near an interface between the metal layer and the semiconductor substrate; and
 - a chiral nanostructure coupled to the substrate or the metal layer, the chiral nanostructure comprising a conducting or semiconducting material and having an inductance; and
 - a bias circuit to apply a bias voltage across the metal layer and the semiconductor substrate to control a capacitance of a tunable capacitor comprising the depletion layer, the chiral nanostructure and the tunable capacitor forming a tunable resonant circuit.
2. The apparatus of claim 1, comprising a control circuit to adjust a resonant frequency of the resonant circuit by controlling the bias circuit to adjust the capacitance of the depletion layer such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz.
3. The apparatus of claim 2 in which the control circuit sweeps the bias voltage from a first voltage to a second voltage to cause the resonant frequency of the resonant circuit to sweep from a first frequency to a second frequency.
4. The apparatus of claim 1, comprising a terahertz transmitter that comprises the terahertz resonator, and a power source to provide electric power to the tunable terahertz resonator, wherein the tunable terahertz resonator converts the electric power into terahertz electromagnetic radiation that is emitted from the terahertz transmitter.
5. The apparatus of claim 1, comprising a terahertz detector that comprises the terahertz resonator, and an amplifier to amplify terahertz radiation received by the tunable terahertz resonator.
6. The apparatus of claim 1 in which the chiral nanostructure comprises a nanocoil.
7. The apparatus of claim 1 in which the bias circuit provides pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.
8. An apparatus comprising:
 - a tunable terahertz resonator comprising:
 - a semiconductor substrate;
 - a plurality of metal regions on the semiconductor substrate, a depletion layer being formed in the semiconductor substrate near an interface between each metal region and the semiconductor substrate, each metal region and corresponding depletion layer and corresponding portion of the semiconductor substrate forming a tunable capacitor; and
 - a plurality of chiral nanostructures each coupled to one of the metal regions, each chiral nanostructure comprising a conducting or semiconducting material and having an inductance, each chiral nanostructure and the corresponding tunable capacitor forming a tunable terahertz resonant circuit; and
 - a bias circuit to provide a bias voltage across each metal region and the semiconductor substrate to control a capacitance of the tunable capacitor to control a resonant frequency of the resonant circuit;

wherein at least two of the plurality of tunable terahertz resonant circuits can be controlled independently of each other.

9. The apparatus of claim 8 in which the chiral nanostructures comprise right-handed chiral nanostructures and left-handed chiral nanostructures, and the terahertz resonator is operable in a first mode in which the number of activated resonant circuits having the right-handed chiral nanostructures is greater than the number of activated resonant circuits having the left-handed chiral nanostructures, and a second mode in which the number of activated resonant circuits having the left-handed chiral nanostructures is greater than the number of activated resonant circuits having the right-handed chiral nanostructures.
10. The apparatus of claim 8 in which the control circuit controls the bias voltages applied to the at least two tunable terahertz resonant circuits that can be controlled independently of each other to independently adjust the resonant frequencies of the at least two resonant circuits.
11. The apparatus of claim 8 in which the bias circuit provides pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.
12. An apparatus comprising:
 - a tunable terahertz resonator comprising:
 - a tunable capacitor; and
 - a three-dimensional chiral nanostructure coupled to the tunable capacitor, the nanostructure having an inductance, the nanostructure and the tunable capacitor forming a resonant circuit; and
 - a bias circuit to apply a bias voltage across the tunable capacitor, the bias voltage controlling a capacitance of the tunable capacitor such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz.
13. The apparatus of claim 12 in which the tunable capacitor comprises a depletion region in a semiconductor substrate.
14. The apparatus of claim 12 in which the nanostructure and the tunable capacitor are aligned along a first direction, the nanostructure having a footprint that is less than 10^{-8} cm² on a surface perpendicular to the first direction.
15. The apparatus of claim 12 in which the bias circuit provides pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.
16. A method of operating a terahertz resonator, the method comprising:
 - applying a bias voltage across a metal layer and a semiconductor substrate to control a thickness of a depletion region near an interface between the metal layer and the semiconductor substrate, the depletion region having a capacitance that is dependent on the thickness of the depletion region,
 - the depletion region being electrically coupled to a chiral nanostructure to form a resonant circuit, the chiral nanostructure being made of a conducting or semiconducting material and having an inductance; and
 - controlling the bias voltage to adjust a resonant frequency of the resonant circuit.
17. The method of claim 16 in which the nanostructure has dimensions selected to cause the nanostructure to have a predetermined inductance such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz when the bias voltage is within a predetermined range.
18. The method of claim 16, comprising receiving a terahertz radiation at the resonant circuit, and processing the received terahertz radiation.
19. The method of claim 18, comprising sweeping the bias voltage from a first voltage level to a second voltage level to

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cause the resonant frequency of the resonant circuit to sweep from a first frequency to a second frequency, and performing spectroscopy on the received terahertz radiation.

20. The method of claim 16, comprising providing electric power to the resonant circuit and causing the resonant circuit to emit terahertz radiation.

21. The method of claim 16, comprising providing pulse voltage signals to the resonant circuit to initiate oscillation of the resonant circuit.

22. A method of operating a terahertz resonator, the method comprising:

applying at least one bias voltage to a plurality of tunable terahertz resonant circuits formed on a semiconductor substrate, each resonant circuit comprising a tunable capacitor electrically coupled to an inductor comprising a chiral nanostructure, the at least one bias voltage being applied to the tunable capacitors to control capacitances of the tunable capacitors,

the chiral nanostructure having dimensions selected to cause the chiral nanostructure to have a predetermined inductance such that the resonant circuit has a resonant frequency in a range between 0.3 to 30 THz when the bias voltage is within a predetermined range; and

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independently controlling the bias voltages applied to at least two of the resonant circuits to independently adjust the resonant frequencies of the at least two resonant circuits.

23. The method of claim 22, comprising providing signals to the at least two independently controlled resonant circuits and emitting terahertz radiation from the at least two independently controlled resonant circuits using at least two different terahertz frequencies.

24. The method of claim 22 in which the nanostructures comprise right-handed chiral nanostructures and left-handed chiral nanostructures that are individually selectable, and the method comprises:

operating the resonant circuits in a first mode by activating resonant circuits having the right-handed chiral nanostructures and de-activating resonant structures having the left-handed chiral nanostructures, and

operating the resonant circuits in a second mode by activating resonant circuits having the left-handed chiral nanostructures and de-activating resonant structures having the right-handed chiral nano structures.

25. The method of claim 22, comprising providing pulse voltage signals to the tunable terahertz resonator to initiate oscillation of the resonator.

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