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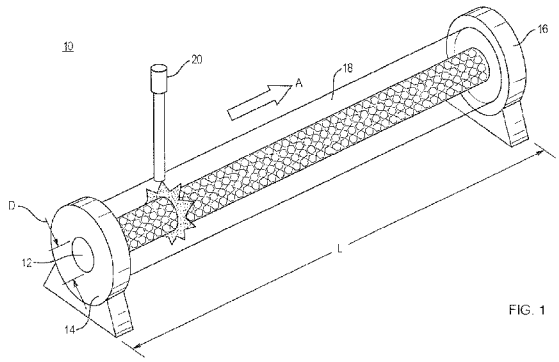


FIG. 1

(57) Abstract: In one aspect, the present invention provides nanosized systems for generating electrical energy based on the use of a chemically reactive composition to generate a thermoelectric wave. For example, the system can include at least one nanostructure (e.g., a carbon nanotube) extending along an axial direction between a proximal end and a distal end. A chemically reactive composition is dispersed along at least a portion of the nanostructure, e.g., along its axial direction, so as to provide thermal coupling with the nanostructure (that is, there is a thermal path, e.g., via contact or otherwise, between the chemical composition and the nanostructure). The chemical composition can undergo an exothermic chemical reaction to generate heat. The system can further include an ignition mechanism adapted to activate the chemical composition so as to generate a thermal wave that propagates along the axial direction of the nanostructure, where the thermal wave is accompanied by an electrical energy wave propagating along the axial direction.

WO 2011/050288 A2

NANOSCALE THERMOELECTRIC WAVE GENERATORS

Related Application

The present application claims priority to provisional application entitled "Nanoscale Thermoelectric Wave Generators" filed on October 22, 2009 and having serial number 61/253,905. This provisional application is herein incorporated by reference in its entirety.

Background

The present invention relates generally to systems and methods for generating electrical and/or pressure pulses, and more particularly, to such systems and methods that generate electrical and pressure pulses by utilizing thermal waves propagating along nanostructures, such as carbon nanotubes.

The miniaturization of electronic devices, network nodes for communications, and remote sensors is driven in part by the favorable scaling of energy requirements for many functions. The reduced energy demand can offset the reduced energy storage capacity. Some critical functions, however, do not scale favorably with size reduction. For example, radio frequency (RF) communication over a practical distance imposes fixed power demand. To further reduce the size of RF communication devices, small power sources will be needed that can produce as much power as currently available power supplies. Moreover, even in systems that benefit from favorable scaling of energy requirements, high power nanosized electrical power sources would permit improved performance and/or sensitivity.

Thus, there is a need for improved systems for generating electrical energy, and particularly for generating electrical pulses having high peak powers for use in miniaturized devices.

Summary

In one aspect, the present invention provides nanosized systems for generating electrical energy based on the use of a chemically reactive composition to generate a thermoelectric wave. For example, the system can include at least one nanostructure extending along an axial direction between a proximal end and a distal end. The

nanostructure can exhibit a thermal conductivity equal or greater than about 500 W/m/K and an electrical conductivity equal or greater than about 10^5 siemens/meter (S/m) along the axial direction. A chemically reactive composition is dispersed along at least a portion of the nanostructure, e.g., along its axial direction, so as to provide thermal coupling with the nanostructure (that is, there is a thermal path, e.g., via contact or otherwise, between the chemical composition and the nanostructure). The chemical composition can undergo an exothermic chemical reaction to generate heat. The system can further include an ignition mechanism adapted to activate the chemical composition so as to generate a thermal wave that propagates along the axial direction of the nanostructure, where the thermal wave is accompanied by an electrical energy wave propagating along the axial direction.

A variety of chemically reactive compositions (compounds) can be utilized in the above system. In some cases, the chemical composition undergoes a decomposition reaction in response to activation so as to generate heat. By way of example, the chemical composition can be cyclotrimethylene-trinitramine (TNA), picric acid, nitrocellulose, trinitrotoluene, JP-8 jet fuel, or gasoline.

In some implementations, the ignition mechanism is adapted to activate the reactive composition in proximity of a proximal end of the nanostructure(s) to undergo a chemical reaction to generate a thermal wave. As the thermal wave propagates axially along the nanostructure it causes the activation of the other portions of the chemical composition, which in turn generates thermal energy that sustains the thermal wave, and a concomitant electrical energy wave, propagating along the nanostructure towards its distal end.

In some cases, the generated electrical energy wave (pulse) can exhibit a peak power as large as about 14 kW/kg or greater.

The ignition mechanism can be implemented in a variety of different ways. For example, the ignition mechanism can include a laser source, e.g., a laser diode that can generate 400 mW of power at a wavelength of 785 nm. Alternatively, the ignition mechanism can generate a high voltage electrical discharge spark, e.g., 3 kV DC and 5 milli-amps, for activating the chemical composition. As another alternative, the ignition mechanism can locally heat the source, e.g., with a wire used as an electrical resistance

heater operating at about 1-3 V DC and about 1-5 amps (the voltage and current depend on the resistance of the wire).

In one embodiment, the system can include an elongated nanostructure such as a carbon nanotube. In some cases, multi-walled carbon nanotube(s) can be employed as the elongated nanostructure. In other implementations, the elongated nanostructure can be nanowire formed, for example, of silicon, boron nitride, nickel silicide, or lead sulfide.

In another embodiment, the system can include a sheet of a material, such as graphene, characterized by two opposed surfaces separated by a thickness of the material forming the sheet (e.g., a thickness less than about 25 nm), where the sheet extends along a longitudinal direction from a proximal end to a distal end. In some implementations, the sheet can exhibit a thermal conductivity equal or greater than about 2000 W/m/K and an electrical conductivity equal or greater than about 10^7 S/m at least along the longitudinal direction.

A chemically reactive composition is disposed on at least a portion of at least one of said surfaces (e.g., it coats the surface) so as to be in thermal coupling with at least that surface. The reactive composition is capable of undergoing a chemical reaction in response to activation to generate heat. The system can further include an ignition mechanism adapted to activate the chemical composition so as to generate a thermal wave propagating longitudinally along the sheet, where the thermal wave is accompanied by a co-propagating wave of electrical energy.

In another aspect, the present invention provides a method of generating electrical energy, which comprises providing a nanostructure (e.g., a carbon nanotube or a sheet having a nanosized thickness) extending along an axial direction with a chemically reactive compound disposed (e.g., dispersed) on at least a portion thereof (e.g., in the form of a coating), where the compound is in thermal contact with the nanostructure. The nanostructure can exhibit a thermal conductivity equal or greater than about 500 W/m/K and an electrical conductivity equal or greater than about 10^5 S/m along the axial direction. A chemical reaction can be initiated in a portion of the chemically reactive compound at a location along the axial direction so as to generate a thermal wave propagating along the nanostructure to cause a chemical reaction in other portions of the reactive compound, thereby generating and sustaining a thermal wave

propagating along the axial direction. The thermal wave is accompanied by an electrical pulse propagating along the axial direction.

Further understanding of the invention can be obtained by reference to the following detailed description and the associated drawings, which are discussed briefly below.

Brief Description of the Drawings

FIGURE 1 schematically depicts a system according to an embodiment of the invention for converting chemical energy into electrical energy,

FIGURES 2A-2C schematically depict an exemplary implementation of the system of FIGURE 1, which includes at least one multi-walled carbon nanotube (MWNT) coated with TNA,

FIGURE 3 schematically depicts a mechanism for initiating a chemical reaction in the coating of the carbon nanotube depicted in the previous figures via a high voltage electrical discharge,

FIGURE 4 shows another exemplary implementation of the system of FIGURE 1 in which a heater and a temperature controller are employed to preheat the coated nanotube prior to initiating an exothermic chemical reaction in the nanotube's reactive coating,

FIGURE 5 schematically depicts an exemplary set-up for detecting thermopower waves generated in a system according to the invention,

FIGURE 6 shows a measured positive voltage pulse generated in a system according to the invention by initiating a chemical reaction in a chemically reactive coating of a plurality of multi-walled carbon nanotubes,

FIGURE 7 schematically depicts an exemplary implementation of a system according to an embodiment of the invention that includes an array of multi-walled carbon nanotubes coated with a chemically reactive composition,

FIGURE 8 schematically depicts an exemplary electronic device in which a system according to the teachings of the invention is incorporated as a power source,

FIGURE 9 schematically depicts a system according to another embodiment of the invention for generating pulsed electrical energy,

FIGURE 10 schematically depicts an exemplary system according to another embodiment of the invention that includes a plurality of carbon nanotubes coated with a reactive composition and a mechanism for *in-situ* replenishment of the reactive coating,

FIGURES 11A and 11B schematically depict a system according to another embodiment of the invention in which the decomposition of a chemically reactive coating of a plurality of carbon nanotubes produces a propulsion force,

FIGURES 12A-12C schematically depict a system according to another embodiment of the invention that includes a sheet of graphene coated with a chemically reactive composition, and

FIGURES 13A and 13B depict measured multiple voltage pulses generated in a prototype system according to an embodiment of the invention.

Detailed Description

In some aspects, the present invention provides systems and methods for converting chemical energy into electrical and/or mechanical energy propagating along nanoscale conduits, such as, nanotubes or nanowires. By way of example, in some cases, a nanostructure can be coated, at least partially, with a chemically reactive compound that can be activated at a location along the nanostructure to undergo an exothermic reaction that generates thermal energy. The nanostructure can provide a

conduit for anisotropic propagation of this thermal energy that can in turn initiate an exothermic reaction in other portions of the coating so as to sustain a thermal wave moving along the nanostructure conduit. The thermal wave is accompanied by a pulse of electrical energy that propagates along the conduit as well. The term "nanostructure," as used herein, refers to a material structure having a size less than about 1 micrometer, in at least one dimension (e.g., in one of x, y, or z dimensions). Similarly, the term "nanosized" is used herein to indicate a size in at least one dimension that is about 1 micrometer, and in some cases less than about 500 nanometers (nm), or less than about 200 nm or less than about 100 nm. In many embodiments, the nanostructure can have an aspect ratio (ratio of length to cross-sectional diameter) that is greater than about 1,000,000. In the embodiments discussed below, various salient features of invention are discussed in connection with carbon nanotubes. It should, however, be understood that the teachings of the invention can also be practiced by employing other types of nanostructures, such as nanowires. The term "carbon nanotube(s)" is known in the art and generally refers to allotropes of carbon exhibiting a nanostructure with a length-to-diameter ratio greater than about 1,000 e.g., in some cases up to about 28,000,000.

FIGURE 1 schematically depicts a system 10 according to an embodiment of the invention for generating an electrical pulse, which includes a multi-walled carbon nanotube 12 that extends along an axial direction (A) between a proximal end 14 and a distal end 16. In this implementation, the number of walls of the multi-walled carbon nanotube ranges from two to about 10, though in other implementations multi-walled carbon nanotubes with a different number of walls can be employed. The exemplary carbon nanotube 12 exhibits a thermal conductivity equal or greater than about 500 W/m/K and an electrical conductivity equal or greater than about 10^6 S/m along the axial direction (A). By way of example, the carbon nanotube can exhibit such a high thermal conductivity at a temperature equal or greater than about 2000 K. In this exemplary implementation, the ratio of the diameter (D) of the carbon nanotube 12 to its length (L), which is herein referred to as the aspect ratio of the nanotube, is less than about 70,000,000, e.g., in a range of about 100,000 to about 50,000,000.

A shell 18 formed of a chemically reactive compound peripherally surrounds the carbon nanotube 10 along the axial direction to form an annular coating around the nanotube. By way of example, the shell can have a thickness in a range of about 4 to

about 20 nanometers. While in this implementation the shell extends axially from the proximal end 14 to the distal end 16 to coat the entire axial extent of the carbon nanotube, in other implementations it can extend axially along only a portion of the carbon nanotube. The chemically reactive compound forming the shell is in thermal coupling with the carbon nanotube 12, e.g., via contact with an outer surface of the carbon nanotube in this implementation. The chemically reactive compound can be activated to undergo an exothermic chemical reaction, e.g., a decomposition reaction, to generate heat. By way of example, the chemically reactive compound can exhibit a thermal conductivity less than about 5 W/m/K.

With reference to FIGURES 2A-2C, in this implementation, the shell 18 is formed of cyclotrimethylene-trinitramine (TNA) and has a thickness in a range of about 6 nm to about 9 nm (e.g., about 7 nm). The TNA can be activated (ignited) to undergo a decomposition reaction that generates heat together with rapidly expanding gaseous decomposition products.

More specifically, referring again to FIGURE 1, the exemplary system 10 includes an ignition mechanism 20 that can activate the reactive compound (e.g., TNA in this implementation) at a selected location along the nanotube, e.g., close to the proximal end in this implementation, to cause its decomposition. In this implementation, the ignition mechanism includes a laser light source that generates radiation capable of igniting the TNA. By way of example, the ignition mechanism can include a laser diode that can generate 400 mW radiation at a wavelength of 785 nm. In some implementations, a single pulse of such a laser directed, e.g., via focusing, to a location along the TNA coating can ignite the TNA at that location. As discussed in detail below, such initial ignition can result in an axially propagating chain reaction along the TNA annular coating to ignite the other portions of the TNA.

Alternatively, the ignition mechanism can include a mechanism for generating a high voltage electrical discharge. For example, FIGURE 3 schematically depicts such a mechanism 22 that includes a wire 24 formed, e.g., of tungsten, that is suspended over a conductive plate 26, e.g., formed of tungsten, with a gap between the wire's tip and the tungsten plate. A high voltage power supply 28 can apply a high voltage, e.g., up to about 3 kV, across the wire tip and the plate to initiate a discharge within the gap. As shown schematically in FIGURE 3, the coated nanotube (in this case TNA coated multi-

walled carbon nanotube) can be attached to the wire's tip at a selected location to be suspended over the plate 26. The power supply can apply a high voltage to the wire to cause an electrical discharge between the coated nanotube and the tungsten plate. The electrical discharge can in turn initiate the chemical reaction in the reactive coating, e.g., a decomposition reaction in the TNA coating.

With reference to FIGURE 4, in some implementations, a heater 32 operating under the control of a temperature controller 34 can be utilized to preheat the coated nanotube, e.g., up to a temperature of about 423 K, prior to initiating an exothermic chemical reaction in the reactive coating. Alternatively, the chemical reaction can be initiated without preheating the carbon nanotube, e.g., it can be initiated at a temperature of about 300 K.

Referring again to FIGURE 1, in use, the initiation of a chemical reaction in the coating, e.g., in the vicinity of the proximal end 14 in this exemplary implementation, can generate heat that will propagate as a thermal wave axially along the carbon nanotube. The heat wave in turn causes the initiation of the chemical reaction in other portions of the chemical coating (a chain reaction), to sustain a reaction wave and an associated heat wave. As each portion of the chemical coating undergoes the chemical reaction it generates heat, which sustains the heat wave as it propagates from the proximal end to the distal end. In some cases, such a sustained reaction wave can move axially along the nanotube at a velocity that can be more than two orders of magnitude greater than the bulk combustion rate of the reactive material forming the coating. For example, a steadily propagating wave with a velocity of 1.2+/- 0.4 m/sec was observed in a prototype multi-walled carbon nanotube that was coated with a TNA with a thickness of about 7 nm. In contrast, the speed of a reaction wave in bulk TNA alone is between 0.2 and 0.5 mm/sec.

Applicants have discovered that this directional thermal wave evolves a corresponding electrical energy wave (herein referred to as a "thermopower wave") along the same direction as the thermal wave, e.g., in the form of a high specific power electrical pulse of constant polarity. With reference to FIGURE 5, such an electrical pulse can be observed, e.g., by electrically contacting an oscilloscope 36 across a carbon nanotube coated with a chemically reactive material (or an array of carbon nanotubes coated with a chemically reactive material as discussed below).

By way of example, as shown schematically in FIGURE 6, the laser initiation of the exothermic reaction at one end of an array of coated carbon nanotubes can result in a voltage peak of the same duration as the reactive wave. The voltage wave is positive for waves emanating from the positive electrode, indicating that the wave is generated by a pulse of majority electronic carriers traveling toward the negative electrode. This thermopower wave is distinct from conventional, static thermopower because of its anisotropic propagation. If a temperature pulse were travelling across the medium generating thermopower, the voltage pulse would change sign, showing an inflection midway and would integrate to zero over the nanotube's length. Further, in such a case, if the reaction were initiated at the middle of the nanotube, the current would reverse. In contrast, the chemically driven thermopower waves generated according to the teachings of the invention exhibit constant polarity in the direction of the reaction. Without being limited to any particular theory, these observations indicate that in the systems according to the teachings of the invention, the majority electrical carriers (e.g., electrons) are entrained in the thermal wave, thereby producing a high electrical power pulse. The electrical pulse can exhibit, for example, a specific power as large as 14 kW/kg.

Carbon nanotubes have a relatively low Seebeck coefficient (e.g., about 80 μV/K) compared with many conventional thermoelectric materials such as bismuth telluride (exhibiting a Seebeck coefficient of about 287 μV/K) or Bi_2Te_3/Sb_2Te_3 superlattices (Seebeck coefficient of about 244 μV/K), although modest increases are observed over the temperature range between about 300 K and about 930 K. Thermopower waves generated according to the teachings of the invention, however, do not necessarily require low phonon and high electron transport rates as the thermal gradient is preserved in the propagation of the wavefront.

In some implementations, rather that utilizing a single nanotube that is at least partially coated with a chemically reactive material, an array of nanostructures, e.g., an array of aligned carbon nanotubes, coated with a chemically reactive material can be employed. By way of example, FIGURE 7 schematically depicts an exemplary implementation of such a system 38 that includes an array 40 of carbon nanotubes 42 (e.g., multi-walled carbon nanotubes) that are substantially aligned along an axial direction (AD). A large fraction of the individual nanotubes, and preferably all of the nanotubes of the array, are at least partially coated with a chemically reactive compound

44, such as TNA discussed above, to form, e.g., a reactive shell that extends axially along the nanotubes. By way of example, in some cases, more than about 70%, or more than about 80%, or more than about 90%, and preferably 100%, of the individual nanotube strands of the array are at least partially coated with the chemically reactive material. In some implementations, the coating extends along the entire length of many, and preferably all, of the individual strands. The number of the carbon nanotubes in the array can vary from one implementation to another. By way of example, the number of the carbon nanotubes in the array can range from about 50,000 to about 50,000,000.

Similar to the previous embodiment, an ignition mechanism 46, e.g., a pulsed laser source, can initiate an exothermic chemical reaction in the chemically reactive shells surrounding the nanotubes, e.g., at a proximal end (P) of the nanotubes. The heat generated by the chemical reaction, e.g., a decomposition reaction of the chemically reactive material, can give rise to a thermal wave and a concomitant electrical pulse propagating along the array of carbon nanotubes.

The electrical pulse can exhibit a high specific power, e.g., about 14 kW/kg or higher. As discussed in more detail below, the high specific power can exhibit an inverse scaling relationship relative to the mass of the array of the coated carbon nanotubes. In other words, the specific power can increase as the mass of the array of the coated carbon nanotube decreases, e.g., over a mass range of about 10^{-2} mg to about 10 mg. This unusual scaling trend can be favorable for powering micro- and nano-scaled devices. Without being limited by any particular theory, the reduction of the specific power as the mass of the array increases can be due to increase in orthogonal heat transfer in the array, which can degraded the axial heat transfer.

Without being limited to any particular theory, the theory of conventional combustion waves can be adapted to describe the nanotube coupled thermal wave. Consider a first order reactive annulus at dimensionless temperature u surrounding a nanotube or nanowire at temperature u_2 where both are thermally coupled via a dimensionless interfacial conductance, γ. The Fourier description of this system is:

$$\frac{\partial u}{\partial \tau} = \frac{\partial^2 u}{\partial \xi^2} + (1-\eta)e^{-1/u} - \gamma_1(u-u_2) \quad (1)$$

$$\frac{\partial u_2}{\partial \tau} = \alpha_0 \frac{\partial^2 u_2}{\partial \xi^2} + \gamma_2(u-u_2) \quad (2)$$

$$\frac{\partial \eta}{\partial \tau} = \beta(1-\eta)e^{-1/u} \quad (3)$$

where η is the extent of chemical conversion of the reactive annulus, α_0 is the dimensionless thermal diffusivity of the nanotube (normalized by that of the annulus), β is the dimensionless inverse adiabatic temperature of the reactive annulus, τ and ξ are dimensionless time and distance. (Here, γ_1 and γ_2 are γ scaled by material properties of the annulus and nanotube, respectively.) A system initially at room temperature ($u = 0.0124$ for TNA) will produce a reactive wave solution if one end is heated to ignition. Numerical solution of (1-3) demonstrates that, since the thermal conductance in the nanotube exceeds that of the reactive annulus, the reaction velocity along the nanotube component is increased substantially, directing the energy along its length. The non-linear nature of the source term causes the reaction velocity to increase disproportionately with an increase in nanotube thermal diffusivity above that of the reactive annulus, creating an amplified thermal wave. The numerical solution can be used in conjunction with the measured reaction velocities to estimate the effective thermal conductances of the MWNT.

The systems according to the teachings of the invention can have a variety of applications. By way of example, the above systems 10 and 38 can be employed as power sources in a variety of devices, especially in miniaturized electronic devices. For example, the system 38 can be utilized to provide high peak power density for intermittent but high load operations, such as emission of modulated radio frequency (RF) signals. By way of example, FIGURE 8 schematically depicts an electronic device 48 in which the above system 38 is incorporated as a power source to supply intermittent electrical pulses to radio frequency (RF) transmitter 50. The RF transmitter 50 converts the received electrical energy to RF energy (e.g., in the form of RF pulses), which is transmitted to a receiver 52.

The teachings of the invention can be implemented in a variety of ways, and are not limited to the above embodiments. By way of example, FIGURE 9 schematically depicts a system 54 according to another embodiment of the invention for generating pulsed electrical energy that includes an array 56 of aligned multi-walled carbon nanotubes 58 extending from a proximal end 60 to a distal end 62 along an axial direction. Rather than coating individual carbon nanotubes of the array with a chemically reactive material, in this embodiment, a coating of a chemically reactive material is applied to an outer surface of the array with the inner carbon nanotubes remaining substantially, or entirely, uncoated. Similar to the previous embodiment, an ignition mechanism 64, e.g., a pulsed laser source, can initiate a chemical reaction in the reactive coating, e.g., at the proximal end, which results in a propagating thermal wave and a concomitant electrical pulse traveling along the nanotubes in the axial direction, in a manner discussed above.

In some embodiments of the invention, the ignition mechanism and the reactive coating are configured such that initiating a chemical reaction at a location along the coating results in generating a pulse without completely depleting the reactive coating. The remainder of the coating can then be utilized to generate one or more additional pulses. Alternatively, a mechanism for replenishing the coating, e.g. *in situ*, can be employed to allow utilizing the same carbon nanotube (or an array of nanotubes) multiple times for generating electrical pulses.

By way of example, FIGURE 10 schematically depicts such a system 66 that includes an array 68 of multi-walled carbon nanotubes 70 extending axially between two electrodes 72 and 74. The carbon nanotubes are circumferentially coated with a hydrocarbon fuel, such as benzene, gasoline, or JP-8 jet fuel, which can undergo an exothermic reaction in response to activation. An ignition mechanism (not shown) can initiate a chemical reaction in the coating, e.g., at the end in proximity of the electrode 72, in a manner discussed above to generate a thermal wave and a concomitant electrical pulse propagating along the carbon nanotube. By way of example, the ignition mechanism can include a pulsed laser that applies a pulse of radiation to the reactive material to initiate a chemical reaction therein. In this implementation, the system can include a fuel reservoir 76 that can replenish the consumed coating to allow generating additional electrical pulses via subsequent activation of the coating. By the way of

example, the fuel from the reservoir can be sprayed onto the carbon nanotubes via a spray mechanism 78 to replenish the coating, thereby allowing the generation of the subsequent electrical pulses.

In some implementations, the coating of the chemically reactive material is not completely consumed via generation of the first pulse, thus allowing the remainder of the coating to be utilized for generating the subsequent pulses. By way of example, the energy of the first laser pulse as well as the type and the thickness of the coating can be configured such that the initiated chemical reaction consumes only a portion of the reactive coating. Subsequently, a second laser pulse can initiate the chemical reaction in the remainder of the coating. This process can be repeated until the entire coating of the chemically reactive material is consumed.

The chemical reaction initiated in the chemically reactive compound can also generate a pressure wave of high energy density. By way of example, the rapidly expanding, gaseous decomposition products from the thermal wave can create a strong pressure pulse that is highly anisotropic. In other words, the pressure pulse provides a thrust along the axial direction of the carbon nanotube(s). Such an anisotropic pressure wave can be utilized in a variety of systems, such as microthrusters, microactuators, micro-pyrovalves or explosive bolts or other connectors as well as shaped and controlled chemical synthesis on the micro-nanoscale.

By way of example, with reference to FIGURES 11A and 11B, a plurality of multi-walled carbon nanotubes can be coated with a chemically reactive compound, e.g., in a manner discussed above. The initiation of a reaction in the compound at one end of the carbon nanotubes can initiate an exothermic chain reaction in the coating of each coated carbon nanotube, which in turn results in a reaction wave propagating along the nanotube, as shown schematically in FIGURE 11B. The rapidly expanding gas generated as a result of the exothermic reaction generates a pressure wave that propels that carbon nanotube along a direction opposite to the direction of the propagating reaction. As discussed above, this propulsion force can be utilized in a variety of systems, such as micro thrusters.

Although the above exemplary embodiments are implemented by employing carbon nanotubes coated with a chemically reactive compound, in other embodiments a sheet of a material exhibiting the requisite thermal and electrical conductivities can be

coated with a reactive compound to convert the chemical energy stored in the coating into one or more electrical pulses. By way of example, with reference to FIGURES 12A, 12B, and 12 C, such a system 78 can include a sheet of graphene 80 that is coated with fuel layer 82 formed of a chemically reactive material, such as TNA. The coated sheet extends longitudinally between two electrodes 84 and 86. The sheet can have a thickness in a range of, e.g., about 0.5 nm to about 25 nm. The lateral dimensions of the sheet can be selected for a specific application. By way of example, the sheet can have a length in a range of about 10 nm to about 1 cm and a width in a range of about 10 nm to about 1 cm. An ignition mechanism 86, e.g., a pulsed laser in this implementation, can initiate a chemical reaction in the coating at one end of the sheet in proximity of one of the electrodes, which results in generation of a thermal wave and a concomitant electrical pulse propagating along the length of the sheet to other electrode. Although in this implementation a graphene sheet is utilized, more generally, a sheet of a material exhibiting a thermal conductivity equal or greater than about 1000 W/m/K and an electrical conductivity equal or greater than about 10^7 S/m in the plane of the sheet, or at least along one dimension of the plane (e.g., the longitudinal direction in this case), can be employed.

The following Example is provided to further illustrate the salient features of the invention and is not intended to necessarily indicate the optimal ways of practicing the invention or optimal results that can be obtained.

Example

To illustrate the feasibility of generating multiple electrical pulses by utilizing the same set of carbon nanotubes, a prototype system was fabricated that included a plurality of multi-walled carbon nanotubes coated with TNA. TNA was coated on several separate positions on MWNT discontinuously, and each ignition caused the chemical reaction only in a specific region of MWNT. After an ignition at one position, TNA coating at other positions was not ignited due to the discontinuity in coating. Hence, the reaction can be initiated multiple times, creating a voltage pulse each time.

By applying successive pulses from a laser operating at a wavelength of 785 nm and a pulse power of 400 mW to the one end of the coated carbon nanotubes, a plurality of electrical pulses were generated as shown in FIGURES 13A and 13B. More

specifically, after the first reaction, the carbon nanotube array survived with a portion of the fuel coating remaining on the array. By repetitive initiation of the chemical reaction in the coating, the remainder of the fuel coating was consumed to generate multiple electrical pulses. As shown in FIGURES 13A and 13B, both negative and positive voltage peaks were generated repeatedly without the change of the carbon nanotube array. The system can be modified to allow supply of fuel to the carbon nanotubes, e.g., to extend the number of electrical pulses that can be generated by utilizing the array.

Those having ordinary skill in the art will appreciate that various modifications can be made to the above embodiments without departing from the scope of the invention.

Claims:

1. A system for generating electrical energy, comprising:

a nanostructure extending along an axial direction between a proximal end and a distal end, said nanostructure exhibiting a thermal conductivity equal to or greater than about 500 W/m/K and an electrical conductivity equal or greater than about 10^5 S/m along said axial direction,

a chemically reactive composition peripherally disposed on at least a portion of said nanostructure along said axial direction so as to be in thermal coupling with said nanostructure, said reactive composition being capable of undergoing a chemical reaction in response to activation to generate heat traveling as a thermal wave along said axial direction,

wherein the thermal wave is accompanied by a wave of electrical energy propagating along said axial direction.

2. The system of claim 1, further comprising an ignition mechanism adapted to activate said chemical composition so as to generate said thermal wave.

3. The system of claim 1, wherein said nanostructure comprises a carbon nanotube.

4. The system of claim 3, wherein said carbon nanotube comprises a multi-walled carbon nanotube.

5. The system of claim 1, wherein said a nanostructure comprises a nanowire.

6. The system of claim 5, wherein said nanowire is formed of any of silicon, boron nitride, nickel silicide, or lead sulfide.

7. The system of claim 1, wherein said nanostructure comprises a sheet having a nanosized thickness.

8. The system of claim 1, wherein said reactive composition undergoes decomposition in response to activation by said ignition mechanism.

9. The system of claim 1, wherein said reactive composition comprises any of cyclotrimethylene-trinitramine, picric amide, picric acid or nitrocellulose.

10. The system of claim 1, wherein said reactive composition peripherally coats said nanostructure substantially from said proximal end to said distal end.

11. The system of claim 10, wherein said ignition mechanism is adapted to activate said reactive composition in proximity of said proximal end to generate a reaction front propagating from the proximal end to the distal end, thereby generating and sustaining a thermal wave and an accompanying electric energy wave propagating from said proximal end to said distal end.

12. The system of claim 1, wherein said ignition mechanism employs light to cause activation of said reactive composition.

13. The system of claim 1, wherein said ignition mechanism employs a high voltage discharge to cause activation of said reactive composition.

14. The system of claim 1, wherein said ignition mechanism employs localized heating to cause activation of said reactive compound.

15. The system of claim 1, wherein said wave of electrical energy comprises an electrical pulse having a peak power of at least about 14 kW/kg.

16. A system for generating electrical energy, comprising,

a sheet of a material characterized by two opposed surfaces separated by a thickness of the material forming the sheet, said sheet extending along a longitudinal direction from a proximal end to a distal end,

a chemically reactive composition surrounding at least a portion of at least one of said surfaces so as to be in thermal coupling with said at least one surface, said reactive composition being capable of undergoing a chemical reaction in response to activation to generate heat,

an ignition mechanism adapted to activate said chemical composition so as to generate a thermal wave propagating longitudinally along the sheet,

wherein said thermal wave is accompanied by a wave of electrical energy propagating longitudinally along the sheet.

17. The system of claim 15, wherein said sheet has a thickness less than about 25 nm.

18. The system of claim 15, wherein said sheet exhibits a thermal conductivity equal or greater than about 1000 W/m/K and an electrical conductivity equal or greater than about 10^7 S/m at least along said longitudinal direction.

19. A method of generating electrical energy, comprising

providing an nanostructure extending along an axial direction and having a coating formed of a chemically reactive compound, said coating being in thermal contact with said nanostructure and said nanostructure exhibiting a thermal conductivity equal or greater than about 500 W/m/K along said axial direction,

initiating a chemical reaction in a portion of said chemically reactive compound at a location along said axial direction so as to generate a heat propagating along said nanostructure to cause a chemical reaction in other portions of said reactive compound, thereby generating and sustaining a heat wave propagating along said axial direction,

wherein said heat wave is accompanied by an electrical pulse propagating along said axial direction.

20. The method of claim 1, wherein said nanostructure comprises a carbon nanotube.

21. The method of claim 1, wherein said nanostructure comprises a sheet having a nanosized thickness.

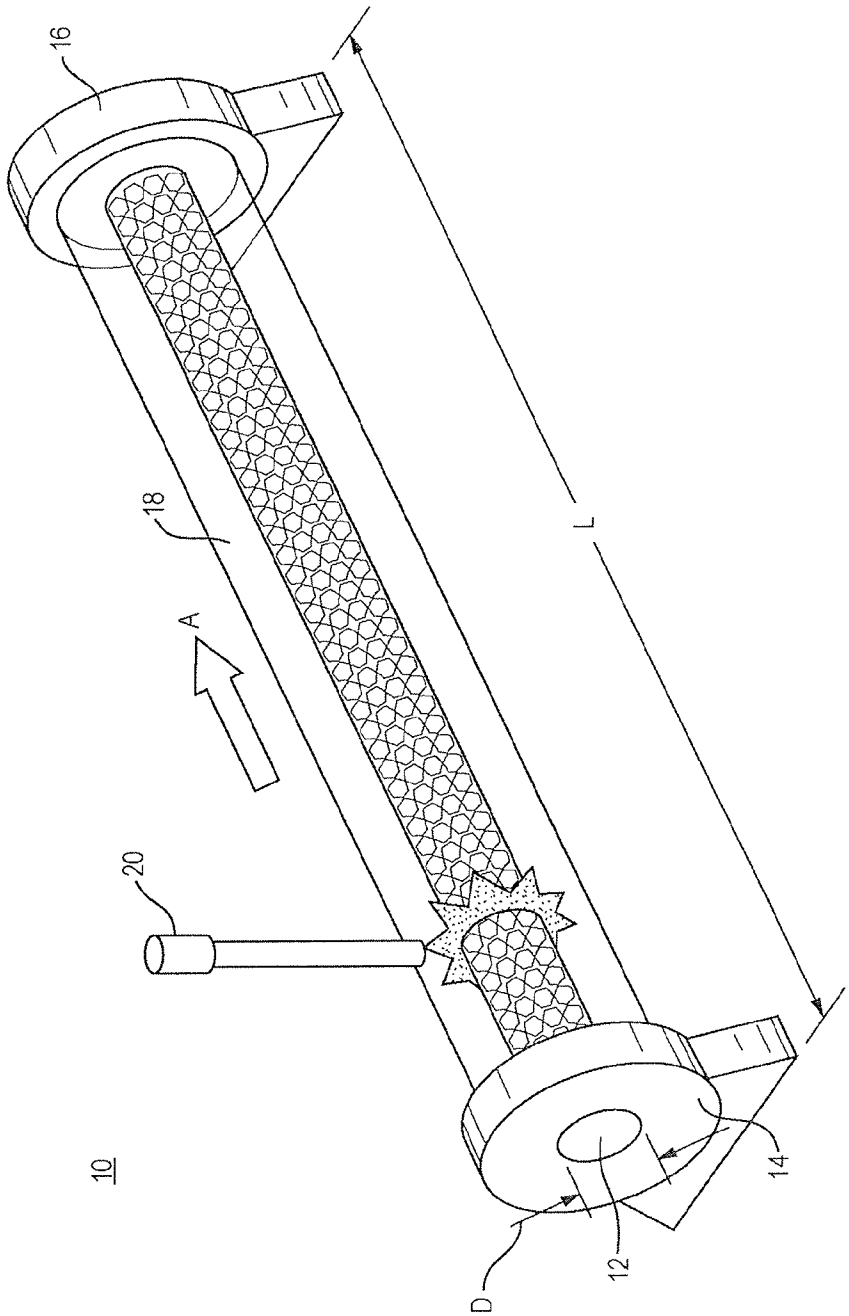


FIG. 1

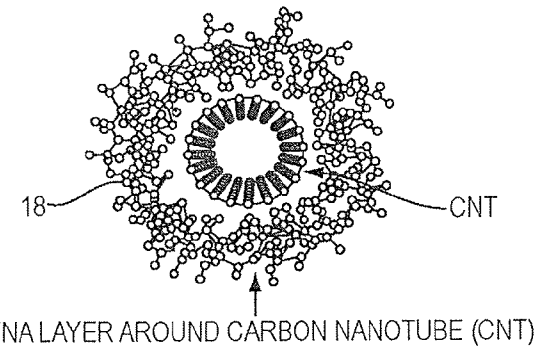


FIG. 2A

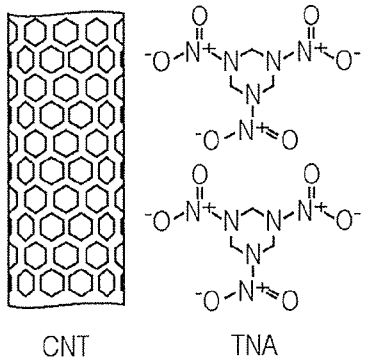


FIG. 2B

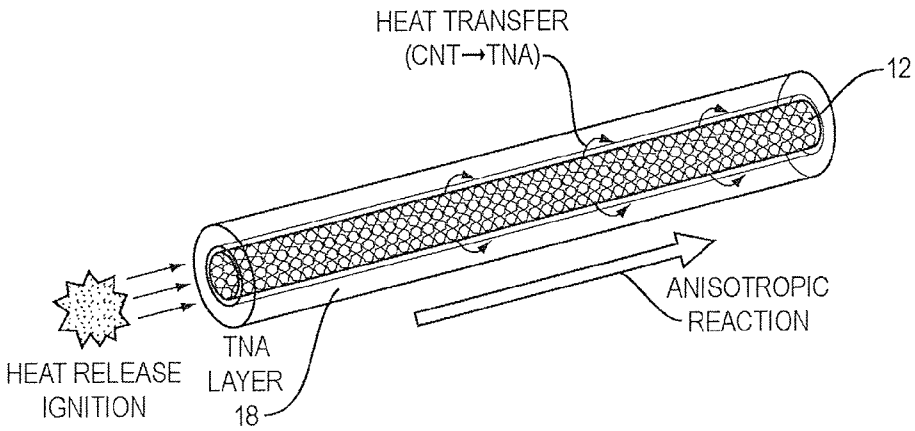


FIG. 2C

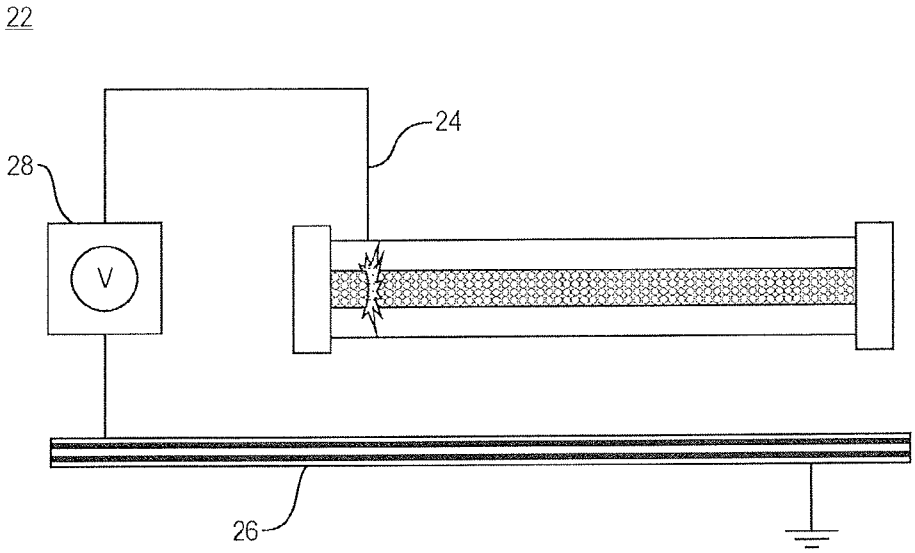


FIG. 3

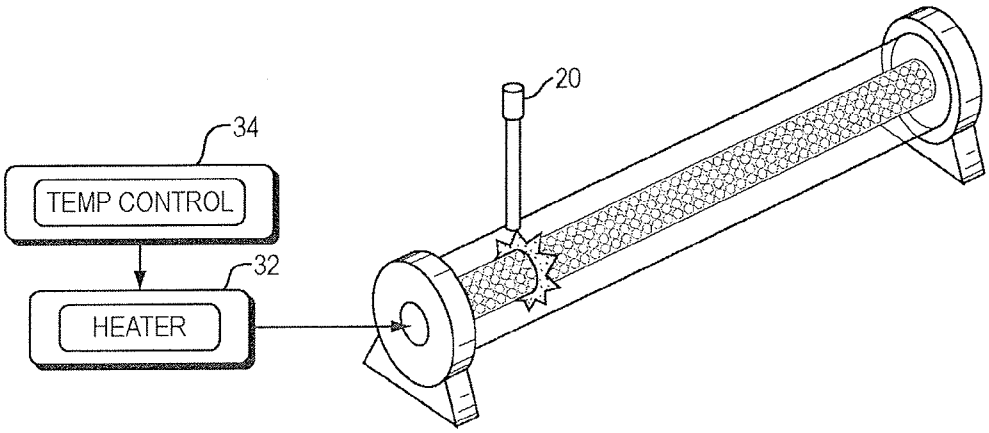


FIG. 4

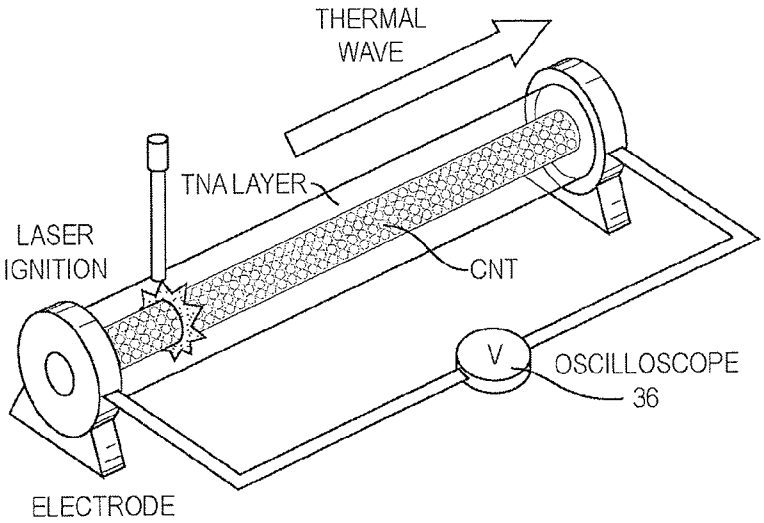

THERMAL
WAVE
TNA LAYER
LASER
IGNITION
CNT
V
OSCILLOSCOPE
36
ELECTRODE

FIG. 5

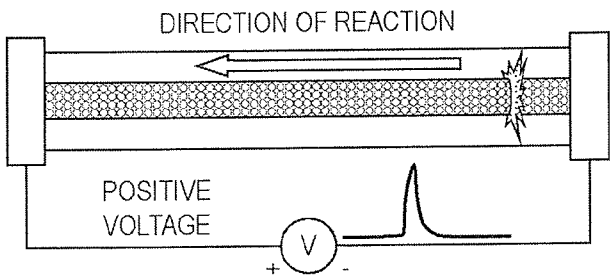

DIRECTION OF REACTION
POSITIVE
VOLTAGE
V
+
-

FIG. 6

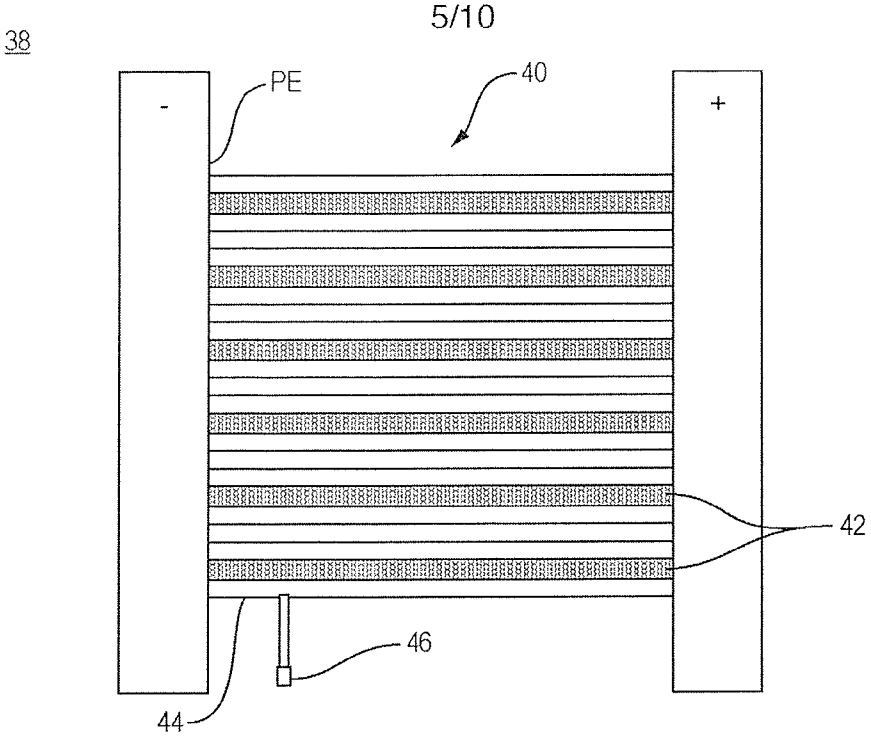

38
PE
40
-
+
42
46
44

FIG. 7

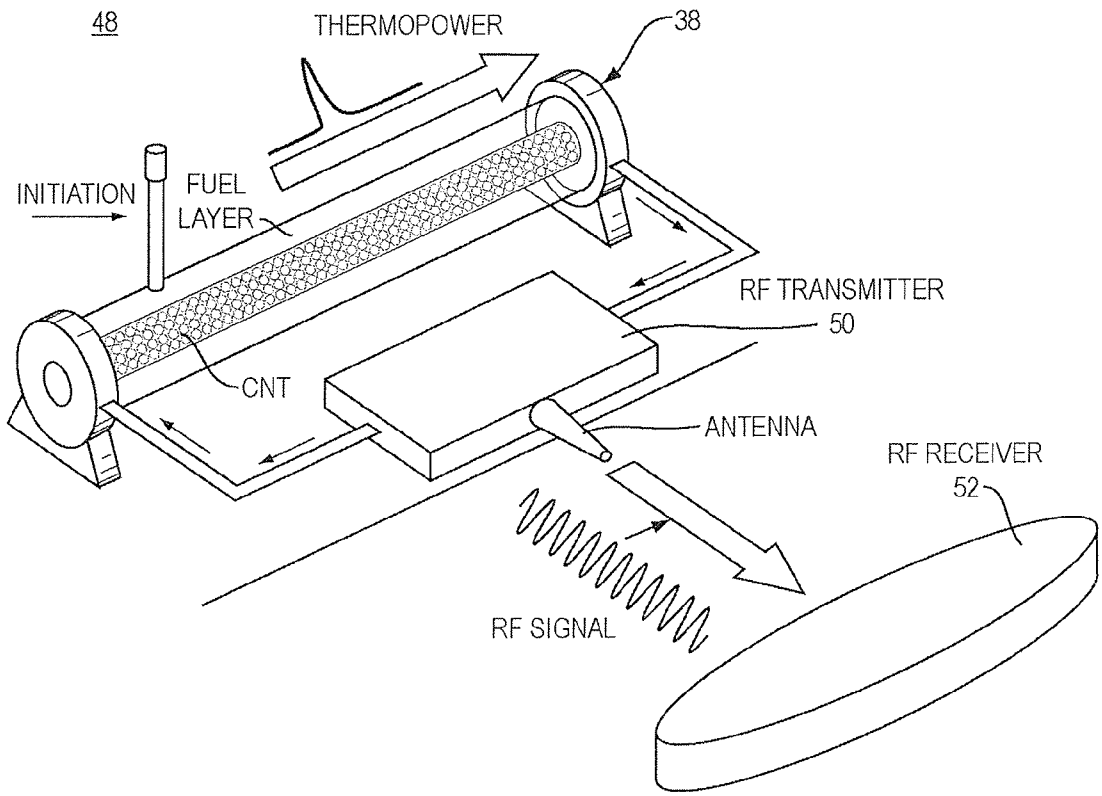

48
THERMOPOWER
38
INITIATION
FUEL
LAYER
RF TRANSMITTER
50
CNT
ANTENNA
RF RECEIVER
52
RF SIGNAL

FIG. 8

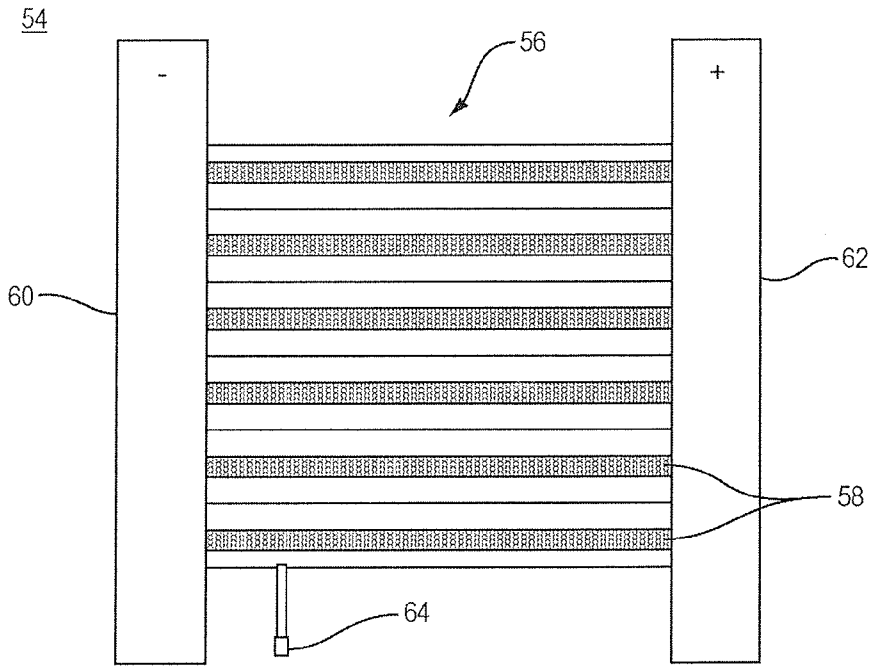


FIG. 9

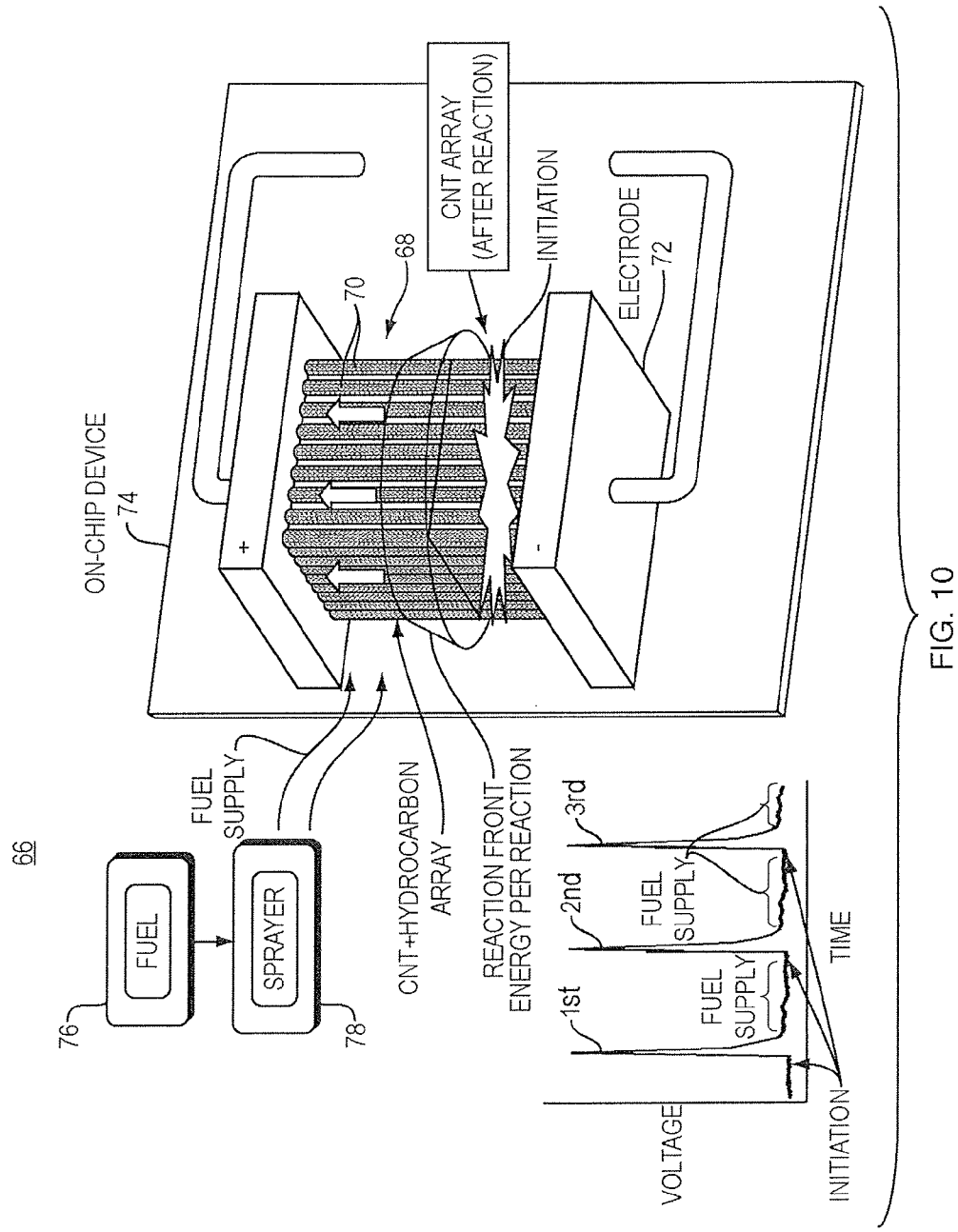

66
FUEL
SPRAYER
76
78
FUEL SUPPLY
CNT+HYDROCARBON ARRAY
REACTION FRONT ENERGY PER REACTION
ON-CHIP DEVICE
74
+
-
70
68
CNT ARRAY (AFTER REACTION)
INITIATION
ELECTRODE
72
1st
2nd
3rd
FUEL SUPPLY
FUEL SUPPLY
VOLTAGE
TIME
INITIATION

FIG. 10

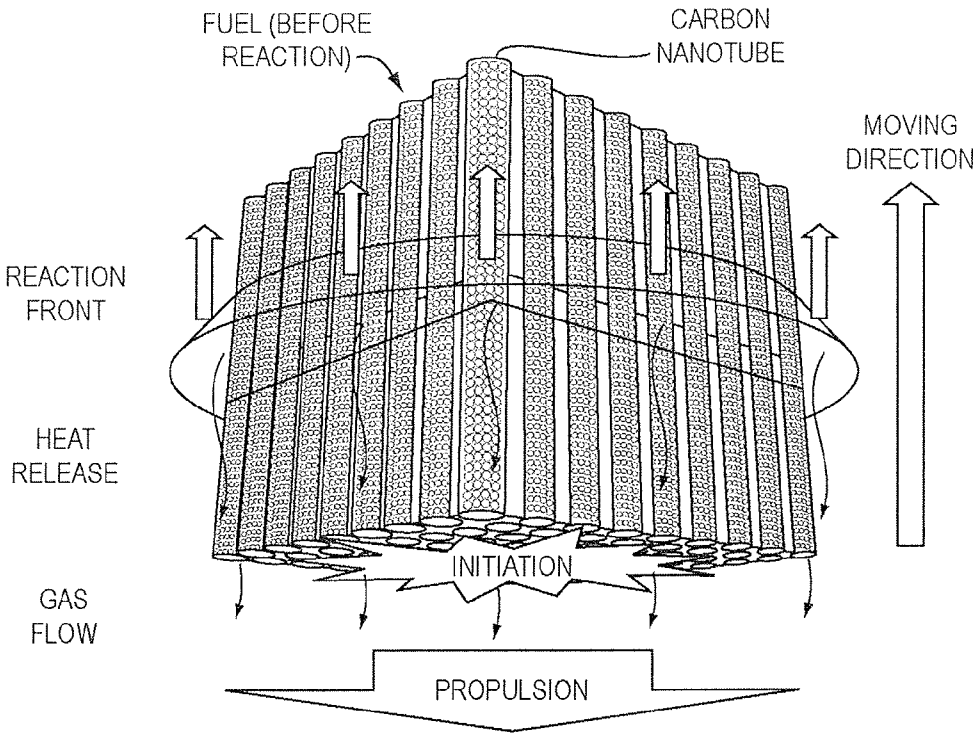


FIG. 11A

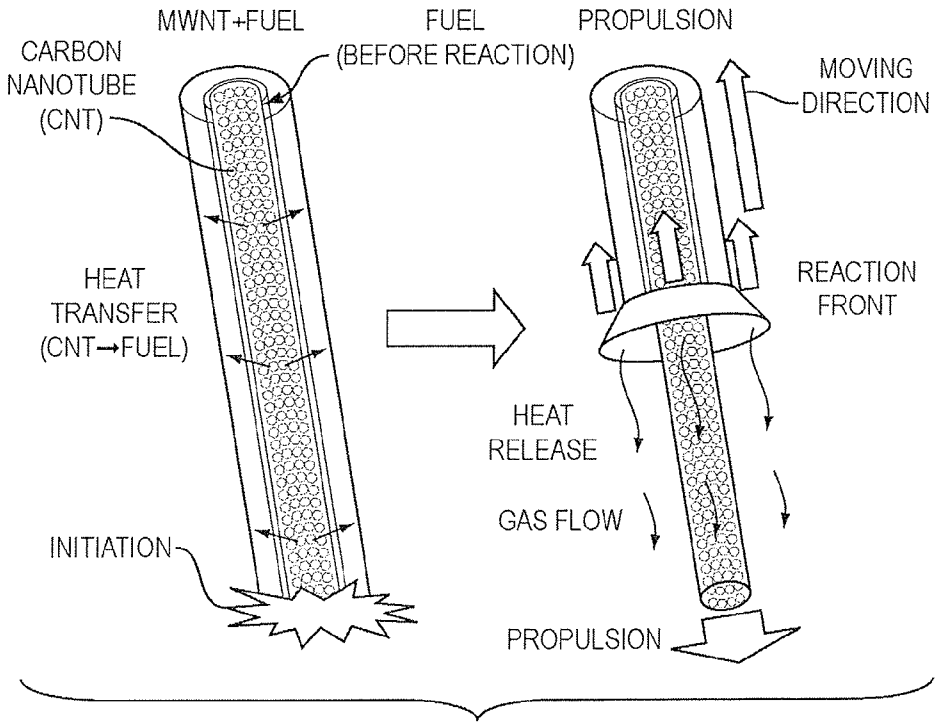


FIG. 11B

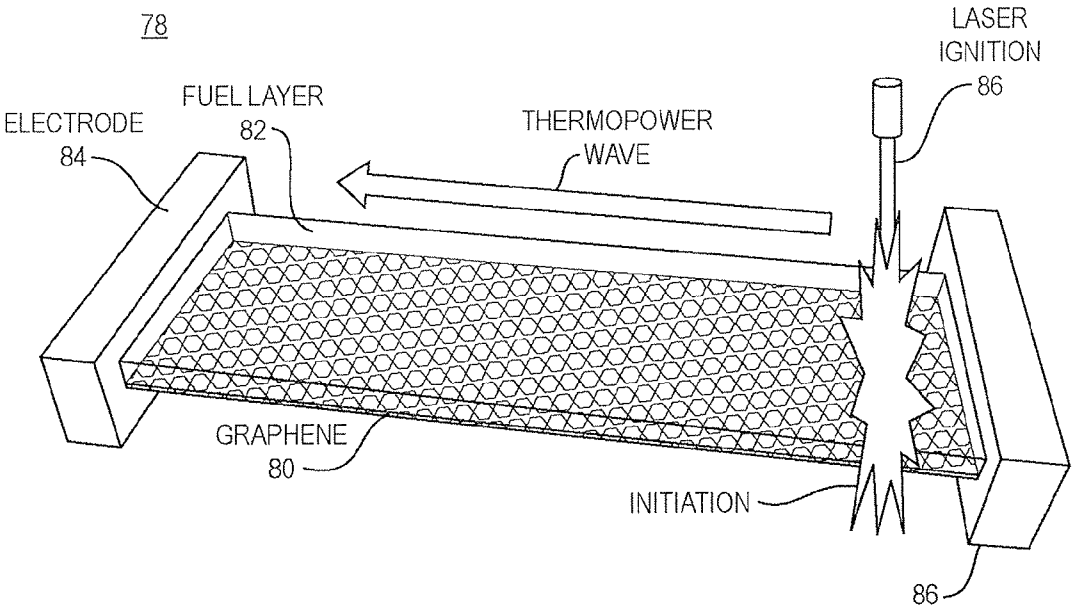


FIG. 12A

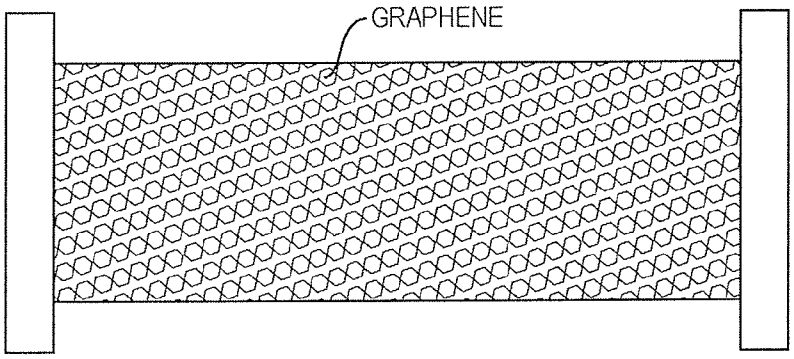


FIG. 12B

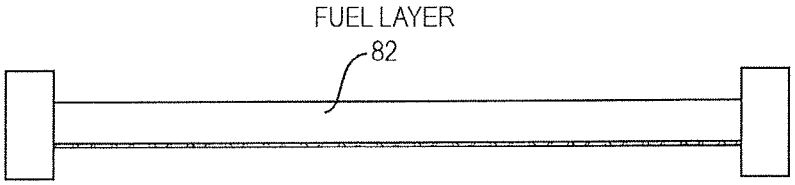


FIG. 12C

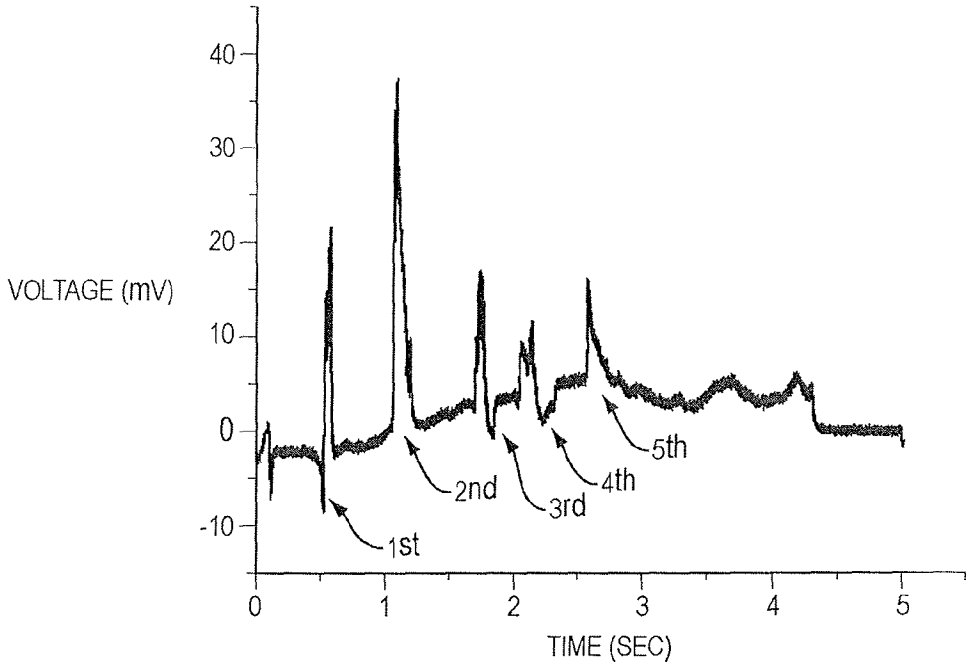


FIG. 13A

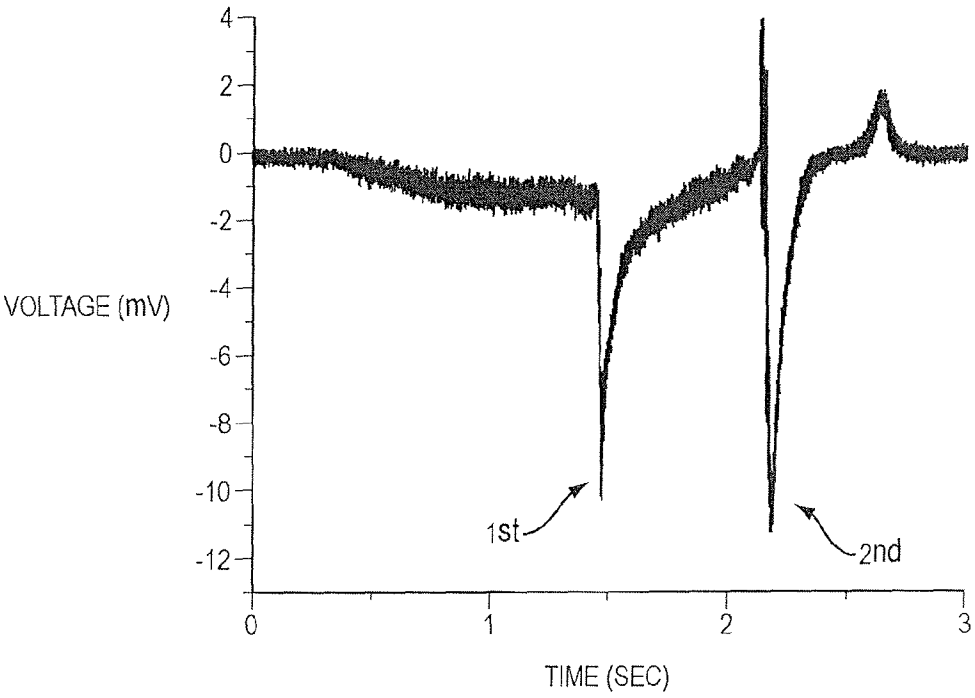


FIG. 13B