

ULTRASONIC TRANSDUCERS AND METHODS FOR PRODUCING AN ULTRASONIC TRANSDUCER

CROSS-REFERENCE TO RELATED APPLICATION

[001] This application claims priority to Singapore patent application no. 10201701352S filed on 21 February 2017, which is incorporated herein by reference in its entirety.

FIELD OF INVENTION

[002] The present invention relates broadly, but not exclusively, to ultrasonic transducers and methods for producing an ultrasonic transducer, for example high frequency ultrasonic transducers using one-dimensional piezoelectric nanostructures (for example as an ultrasonic sensing and/or generating element) and methods for producing such high frequency ultrasonic transducers.

BACKGROUND

[003] High frequency ultrasonic transducers with operation frequency higher than 20 MHz are demanded for high resolution biomedical imaging and non-destructive testing. The resolution of ultrasonic imaging increases with the center frequency and bandwidth (range of frequency) of the ultrasonic transducer. For example, ultrasonic transducer operating at frequency lower than 20 MHz can only resolve blood arteries (diameter from 100 μm to 1 mm) in ultrasonic imaging. However, high frequency ultrasonic transducer operating at frequency higher than 20 MHz is capable of resolving blood arteriole (typical diameter of 30 μm), or even blood capillaries (typical diameter of 8 μm) if operation frequency can be increased to higher than 100 MHz in ultrasonic imaging. In addition, a broad bandwidth (>80 %) is critical to achieving such high resolution as the resolution of ultrasonic imaging increases with bandwidth. Hence, the development of piezoelectric elements for high frequency ultrasonic transducers with good sensitivity and broad bandwidth is crucial to advancing ultrasonic imaging and expanding the relevant applications.

[004] Piezoelectric ceramics such as lead zirconium titanate (PZT) have been commonly used as a sensing and/or generating element for ultrasonic transducers due to their high electromechanical coupling factor. However, these piezoelectric ceramics

have very high acoustic impedance (Z) of above 34 Mrayl as compared to water and human body (which generally is in a range between 1.5 and 2 Mrayl). Such acoustic mismatch may cause low transmission (T) of ultrasonic wave at the piezoelectric element/water interface and deteriorated ultrasonic signals. Although an acoustic matching layer can be introduced to improve the transmission of ultrasonic wave between piezoelectric sensing element with surrounding medium, the attenuation within the acoustic matching layers and the specific thickness of the acoustic matching layer designed for certain frequency limit the sensitivity and bandwidth of the resulting ultrasonic transducer, particularly for high frequency operation. In addition, the fabrication of a matching layer for high frequency ultrasonic transducer is very challenging due to the strict requirement for materials with specific acoustic impedance. In contrast, piezoelectric polymers have acoustic impedance which much better matches with water and human tissue, but they generally have weaker piezoelectric effect.

[005] In order to solve these problems, the piezoelectric composites consisting of a polymer matrix and one-dimensional piezoelectric pillars (which are usually made of piezoelectric ceramics) with 1-3 configuration may be used. The 1-3 piezoelectric composites generally have improved acoustic match with water and human body due to the use of soft polymer matrix. Studies have also shown that the piezoelectric performance of the piezoelectric composites increases with the aspect ratio (length-to-width) of the individual one-dimensional piezoelectric pillars. Hence, the 1-3 piezoelectric composites generally have higher piezoelectric performance due to the high aspect ratio of individual one-dimensional piezoelectric pillars in 1-3 composite.

[006] However, the development of such composite ultrasonic transducers for high frequency ultrasonic applications (> 20 MHz) is limited by the desired small dimensions of one-dimensional piezoelectric pillars, narrow pitches between the one-dimensional piezoelectric pillars and large number of individual one-dimensional piezoelectric pillars. The requirements in one-dimensional piezoelectric pillars are to ensure high aspect ratio for optimum piezoelectric performance and avoid cross-talk between the one-dimensional piezoelectric pillars. For example, at 30 MHz, one-dimensional piezoelectric pillars should have width of less than 10 μm and the gaps between the one-dimensional piezoelectric pillars less than 5 μm . Further refined composite structure is required for further improving the performance. However, such requirements in small dimensions are very challenging to be overcome by using conventional ceramic processing methods.

[007] As disclosed herein, these limitations in conventional 1-3 piezoelectric composite ultrasonic transducers can be overcome by using one-dimensional piezoelectric nanostructures to produce ultrasonic transducers for high frequency operation, in which the dimensions of the individual piezoelectric sensing and/or generating elements are in the sub-micrometer range and can be used for high frequency ultrasonic transducer operating at frequency up to 100 MHz, or even higher frequency.

[008] Previously, producing high frequency ultrasonic transducer with one-dimensional piezoelectric nanostructures was not feasible. The scientific studies in the prior art focus on very localized piezoelectric characterization of individual one-dimensional piezoelectric nanostructures, which is impractical to be directly applied in high frequency ultrasonic transducer. Major challenges of using one-dimensional piezoelectric nanostructure for producing any practically useful ultrasonic transducers include obtaining a relatively large area of multiple vertically aligned one-dimensional piezoelectric nanostructures, designing the ultrasonic transducers whereby a plurality of piezoelectric nanostructures are appropriately organized, electrically connected and integrated into the ultrasonic transducer assembly with collective and constructive output from individual piezoelectric nanostructures for achieving optimum performance at high frequency. Another unknown factor is if potential electrical impedance mismatch between the one-dimensional piezoelectric nanostructures and electronics will make the ultrasonic transducer operation not practical.

[009] A need therefore exists to provide high frequency ultrasonic transducers with operation frequency higher than 20 MHz (and even more than 100 MHz) for high resolution biomedical imaging and non-destructive testing, and the methods for producing the said high frequency ultrasonic transducers.

SUMMARY

[0010] According to a first aspect, there is provided an ultrasonic transducer including: a first electrode; a second electrode; and a plurality of piezoelectric one-dimensional nanostructures, each piezoelectric nanostructure having a first end coupled to the first electrode, a second end coupled to the second electrode, a diameter of less than 500 nm, and a length of at least twice the diameter. The one-dimensional piezoelectric nanostructures have significantly improved piezoelectric

performance properties than monolithic film and improved acoustic impedance match for improved acoustic transmission.

[0011] According to a second aspect, there is provided a method for producing an ultrasonic transducer, the method including: forming a plurality of piezoelectric nanostructures using a template based method, each piezoelectric nanostructure having a diameter of less than 500 nm, and a length of at least twice the diameter; providing a first electrode coupled to respective first ends of the plurality of piezoelectric nanostructures; and providing a second electrode, wherein respective second ends of the plurality of piezoelectric nanostructures are coupled to the second electrode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Embodiments and implementations are provided by way of example only, and will be better understood and readily apparent to one of ordinary skill in the art from the following written description, read in conjunction with the drawings, in which:

[0013] Figures 1A, 1B, and 1C show transducers according to an embodiment;

[0014] Figures 2A, 2B, 2C, 2D, and 2E show piezoelectric nanostructures arrays according to an embodiment;

[0015] Figure 2F shows an illustration of a method for manufacturing a high frequency transducer according to various embodiments;

[0016] Figure 3 shows a schematic illustration of an electrical poling configuration of the one-dimensional piezoelectric nanostructures;

[0017] Figure 4 shows a schematic illustration of a high frequency ultrasonic transducer testing setup operating in echo mode;

[0018] Figure 5A shows a diagram illustrating a time domain signal, and Figure 5B shows a diagram illustrating a Fourier spectrum of the response of high frequency ultrasonic transducer using P(VDF-TrFE) nanotubes as one-dimensional piezoelectric nanostructures;

[0019] Figure 6 shows a schematic illustration of a high frequency ultrasonic transducer testing setup operating in transmission mode;

[0020] Figure 7A shows a diagram illustrating a time domain signal of the commercial ultrasonic transducer and a time domain signal of the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer according to various embodiments operating in transmission mode according to various embodiments, and Figure 7B shows a diagram illustrating a Fourier spectrum of the commercial ultrasonic transducer and a Fourier spectrum of the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer according to various embodiments operating in transmission mode;

[0021] Figure 8A shows a diagram illustrating time domain signals of ultrasonic transducers using one-dimensional piezoelectric nanostructures with different length;

[0022] Figure 8B shows a diagram of Fourier spectra of the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer with different lengths and center frequencies operating in echo mode;

[0023] Figure 8C shows an illustration of a theoretical resolution against the center frequency of ultrasonic transducer, wherein a horizontal axis indicates center frequency, and a vertical axis indicates a resolution.

[0024] Figure 9A and Figure 9B show schematic illustrations of a linear array of high frequency ultrasonic transducers;

[0025] Figure 10 shows a top view of a schematic illustration of a two-dimensional array of high frequency ultrasonic transducers;

[0026] Figure 11 shows a schematic illustration of a high frequency photoacoustic imaging testing setup;

[0027] Figure 12A shows a diagram of a time domain signal of the commercial transducer and P(VDF-TrFE) nanotubes high frequency ultrasonic transducer operating in photoacoustic sensing mode;

[0028] Figure 12B shows a diagram illustrating Fourier spectra of the signals shown in Figure 12A;

[0029] Figure 12C shows a photoacoustic image obtained by the P(VDF-TrFE) nanotube high frequency ultrasonic transducer;

[0030] Figure 13A and 13B show area scan images of the copper wires using a commercial ultrasonic transducer and using the P(VDF-TrFE) nanotube ultrasonic transducer according to various embodiments;

[0031] Figure 13C and 13D show the cross-section analysis of the area scan images and the lateral resolution for commercial ultrasonic transducer and focused P(VDF-TrFE) nanotube ultrasonic transducer, respectively.

[0032] Figure 14 shows an illustration of a scanning ultrasonic imaging setup using focused nanotube ultrasonic transducer and the resulting image of a sample; and

[0033] Figure 15 shows an illustration of a method for producing an ultrasonic transducer in accordance with an embodiment.

DETAILED DESCRIPTION

[0034] Embodiments will be described, by way of example only, with reference to the drawings. Like reference numerals and characters in the drawings refer to like elements or equivalents. It is the intent of present embodiments to present high frequency transducers with high bandwidth and high resolution.

[0035] In accordance with a present embodiment, a high frequency ultrasonic transducer using one-dimensional piezoelectric nanostructures as an ultrasonic sensing and/or generating element is provided.

[0036] High frequency ultrasonic transducers herein refer to any acoustic sensors and/or generator that sense and/or generate ultrasonic signal with frequency higher than 20 MHz. Such high frequency ultrasonic transducers may be used for biomedical imaging and non-destructive testing (NDT). One-dimensional nanostructures herein refer to any structures with outer dimension, such as diameter for cylindrical structure, or width for a rectangular structure, less than 500 nm, and aspect ratio (length-to-diameter/width) of more than 2, preferably more than 5 (e.g. fibers or fibrils, wires,

tubes and rods). Ultrasonic sensing and generating element herein refers to a piezoelectric element used in the ultrasonic transducer to convert ultrasonic wave to electrical signals and vice versa.

[0037] The high frequency ultrasonic transducers include an ultrasonic sensing and/or generating element, electrodes, a backing, and a housing. The high frequency ultrasonic transducers are able to detect ultrasonic wave generated by the same high frequency ultrasonic transducer (echo mode), or from a second ultrasonic transducer (transmission mode), or from other sources (e.g. light induced ultrasound in photoacoustic and laser ultrasonic cases.). The one-dimensional piezoelectric nanostructures are vertically aligned to form an array with the electric polarization along the long axis of the nanostructures. The sensing and/or generating element of the ultrasonic transducer includes the said one-dimensional piezoelectric nanostructures. Electrodes are formed on both ends of the one-dimensional piezoelectric nanostructures, a backing is formed on one end of the said one-dimensional piezoelectric nanostructures array, and a housing enclosing the backing. The present embodiment utilizes the improved piezoelectric properties of one-dimensional piezoelectric nanostructures to produce high frequency ultrasonic transducers with enhanced sensitivity and bandwidth.

[0038] Figure 1A shows a high frequency ultrasonic transducer 100 using one-dimensional piezoelectric nanostructures as ultrasonic sensing and/or generating element. The high frequency ultrasonic transducer 100 includes a plurality of one-dimensional piezoelectric nanostructures 104 which sense and/or generate ultrasonic waves with a frequency higher than 20 MHz. The high frequency ultrasonic transducer 100 furthermore includes two electrodes (a top electrode 102 and a bottom electrode 106), a backing 112 and a housing 114. The bottom electrode 106 is connected to a female connector as the housing 114 through an electrical wire 108 using silver epoxy 110. The two electrodes 102 and 106 are formed on the front and back ends of the one-dimensional piezoelectric nanostructures 104 and the backing 112 is formed on the back side of the back end electrode (in other words: of the bottom electrode 106). When the one-dimensional piezoelectric nanostructures 104 are hit by a high frequency ultrasonic wave, the one-dimensional piezoelectric nanostructures 104 deform at a frequency corresponding to that of the ultrasonic wave, thereby generating a voltage signal across the two electrodes 102 and 106 due to the direct piezoelectric effect and the voltage signal is captured by the associated electrical sensing system connected to the two electrodes 102 and 106. Thus, the transducer 100 is configured to work as a

high frequency ultrasonic sensor. When an external high frequency A.C. voltage signal is applied across the two electrodes 102 and 106, the one-dimensional piezoelectric nanostructures 104 deform at the corresponding frequency due to the converse piezoelectric effect and generate ultrasonic wave into the surrounding medium. Thus, the ultrasonic transducer 100 is configured to operate as a high frequency ultrasonic generator.

[0039] Figure 1B shows a focused high frequency ultrasonic transducer 116 in which (instead of parallel one-dimensional piezoelectric nanostructures 104 as shown in Figure 1A) curved one-dimensional piezoelectric nanostructures 104', and an accordingly curved top electrode 102' are provided.

[0040] Figure 1C shows a photograph 118 of a transducer according to an embodiment.

[0041] The one-dimensional piezoelectric nanostructures 104 may be fabricated with a template based method using ordered anodized alumina membrane as shown in illustration 200 of Figure 2A illustrating a top view of a one-dimensional piezoelectric nanostructures array, illustration 204 of Figure 2B illustrating a cross section side view of a one-dimensional piezoelectric nanostructures array, and illustration 208 of Figure 2C illustrating a cross section of individual one-dimensional piezoelectric nanostructure.

[0042] The piezoelectric materials used to form the one-dimensional piezoelectric nanostructures may include, but are not limited to, poly(vinylidene fluoride) (PVDF), or poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)). The piezoelectric polymers solutions or melts are filled into the one-dimensional pores of an ordered anodized alumina membrane 202, wherein the pore sizes of the ordered anodized alumina membrane 202 determine the dimensions of the one-dimensional piezoelectric nanostructures 104. The pore sizes of the ordered anodized alumina membrane 202 can be controlled by the anodization conditions, which include types of anodization acid, temperature, duration of anodization and post-anodization etching to produce pores with diameter ranging from 25 nm to 500 nm and depth ranging from 50 nm to 100 μm . The ordered anodized alumina membrane 202 is partially removed by controlled chemical etching to expose the one-dimensional piezoelectric nanostructures and separate the one-dimensional piezoelectric nanostructures to be aligned vertically without substantial bundling for forming an array of the one-dimensional structures. The vertically aligned one-dimensional piezoelectric

nanostructures 104 can be formed using a flat ordered anodized alumina membrane to produce a non-focused high frequency ultrasonic transducer, or can be formed using a curved ordered anodized alumina membrane to produce a focused high frequency ultrasonic transducer with a focal length equal to the radius of the curvature of ordered anodized alumina membrane.

[0043] The one-dimensional piezoelectric nanostructures 104 are vertically aligned forming an array as shown in Figures 2A and 2B. The one-dimensional piezoelectric nanostructures 104 include a hollow core (which form nanotube structures as shown in Figures 2A, 2B, or 2C), or a solid core, which form nanorod structures (not shown in Figures 2A, 2B, or 2C). As shown in Figure 2C, the individual one-dimensional piezoelectric nanostructure 104 may have an external diameter (x) of less than 500 nm and an aspect ratio (length-to-diameter ratio, y_1/x) of more than 2, preferably more than 5. Figure 2B shows that a layer of piezoelectric residue film 206 that is made of the same piezoelectric polymer as one-dimensional piezoelectric nanostructures 104 may optionally exist at one end of the one-dimensional piezoelectric nanostructures 104 with the film thickness (y_2), preferably less than the length of the one-dimensional piezoelectric nanostructures (y_1).

[0044] Figure 2D shows a microscopic top view 210 of Piezoelectric P(VDF-TrFE) nanotubes. Figure 2E shows a microscopic top side view 212 of Piezoelectric P(VDF-TrFE) nanotubes.

[0045] Figure 2F shows an illustration 214 of a method for manufacturing a high frequency transducer according to various embodiments. Using piezoelectric polymer solution or melt filling, like illustrated by arrow 216, the one-dimensional piezoelectric nanostructures 104 may be formed. Electric polarization 218 may be provided between the top electrode 102 and the bottom electrode 106.

[0046] The center frequency of the high frequency ultrasonic transducer 100 using one-dimensional piezoelectric nanostructures 104 is determined by resonance frequency of the one-dimensional piezoelectric nanostructures 104, which depends on the speed of sound and the dimension of the said piezoelectric nanostructures 104. For example, the half-wavelength fundamental resonance frequency in longitudinal mode of the one-dimensional piezoelectric nanostructures 104 can be described by the following equation:

$$f_0 = \frac{v}{2y_1}$$

where f_0 is the half-wavelength fundamental resonance frequency, v is the speed of sound and y_1 is the length of the one-dimensional piezoelectric nanostructures 104.

[0047] Figure 3 show a schematic illustration 300 of an electrical poling configuration of the one-dimensional piezoelectric nanostructures 104. The top electrode 102 is formed on the exposed end of the one-dimensional piezoelectric nanostructures 104 and the bottom electrode 106 is formed on another end of the one-dimensional piezoelectric nanostructures 104 with piezoelectric residue film 206 as shown in Figure 3, which correspond to the electrodes 102 and 106 at the front and back ends of the one-dimensional piezoelectric nanostructures 104. The top electrode 102 and the bottom electrode 106 may include (or may be made from) gold-chromium, conductive polymer (poly(3,4-ethylenedioxythiophene)-polystyrene sulfonate (PEDOT:PSS)) or silver. For the formation of gold-chromium electrodes, a layer of chromium with thickness preferably more than 5 nm followed by a layer of gold with thickness preferably no less than 50 nm are deposited on the one-dimensional piezoelectric nanostructures using e-beam evaporation or sputtering. For the formation of conductive polymer (PEDOT:PSS) electrodes, the conductive polymer solution is spin-coated on the one-dimensional piezoelectric nanostructures. For the formation of silver electrode, the silver epoxy is direct-printed on the one-dimensional piezoelectric nanostructures 104. The top electrode 102 and the bottom electrode 106 may include (or may be made from) the same electrode materials or different electrode materials, such as top electrode 102 may be a gold/chromium electrode, while the bottom electrode 106 may be a silver epoxy electrode. The bottom electrode 106 may be patterned as shown in Figure 3, and may define the active area of the one-dimensional piezoelectric nanostructures 104 for ultrasonic wave sensing and/or generating. The one-dimensional piezoelectric nanostructures 104 are poled by applying an electric field 304 across the top electrode 102 and the bottom electrode 106 using a direct current (DC) voltage source 302.

[0048] A mechanical scanning mechanism may be provided for ultrasonic imaging using the single transducer made with the one-dimensional piezoelectric nanostructures 104 as the ultrasonic wave sensing and/or generating element. Alternately, an array of transducers may be provided using the one-dimensional piezoelectric nanostructures 104 for ultrasonic imaging without mechanical scanning. The bottom electrode 102 or the top electrode 106 may be patterned to form a linear array or a two-dimensional array of high frequency ultrasonic transducers. The patterned electrodes may be connected to an external processing unit including a

plurality of independent channels to process ultrasonic wave signals from individual high frequency ultrasonic transducers separately. The ultrasonic wave signals obtained from a linear array of ultrasonic transducers can form two-dimensional ultrasonic images, and a two-dimensional array of ultrasonic transducers can form three dimensional ultrasonic images.

[0049] In an embodiment, a plurality of poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes are used as the one-dimensional piezoelectric nanostructures, and are used as ultrasonic sensing and/or generating element for the high frequency ultrasonic transducer. The high frequency ultrasonic transducer may be used for echo mode ultrasonic testing, involving both ultrasonic wave sensing and generating.

[0050] To produce the one-dimensional piezoelectric nanostructures 104, a one-end sealed ordered anodized alumina membrane with pore size 300 – 350 nm and depth of 4 μm is first be fabricated using a two-step anodization method. The two-step anodization may be performed on high purity Al foil in phosphoric acid under a constant applied voltage of 180 V. The pores of ordered anodized alumina membrane are enlarged by chemical etching in 5 wt% phosphoric acid solution to produce the desired pore sizes. A 10 wt% P(VDF-TrFE) (72/28) solution is prepared by dissolving the P(VDF-TrFE) pellets in a mixed solvent of dimethyl-formamide (DMF) and acetone. The P(VDF-TrFE) solution is then spin-coated on the open end of the ordered anodized alumina membrane and dried at 100 °C. The sample is heated to 220 °C to melt the polymer. The polymer melt wets the ordered anodized alumina membrane and fills into the pores by capillary force. The deposition is repeated to obtain the desired nanotube wall thickness. A plurality of P(VDF-TrFE) nanotubes are produced as the one-dimensional piezoelectric nanostructures embedded in ordered anodized alumina membrane, attached to a residual P(VDF-TrFE) polymer film.

[0051] A bottom electrode including a layer of chromium with thickness 5 nm and a layer of gold with thickness 50 nm is deposited on the side with the residue polymer film by e-beam evaporation. The bottom electrode is connected to a female connector as housing through an electrical wire using silver epoxy. An epoxy is filled into the empty space of the housing to form a backing for the one-dimensional piezoelectric nanostructures. Residual Al foil is removed by chemical etching using copper chloride solution (in hydrochloric acid). The one-dimensional piezoelectric nanostructures are exposed by controlled chemical etching of the ordered anodized alumina membrane in phosphoric acid solution. The top electrode comprising a layer of chromium with

thickness of 5 nm and a layer of gold with thickness of 50 nm is deposited on the exposed end of the one-dimensional piezoelectric nanostructures by e-beam evaporation. The one-dimensional piezoelectric nanostructures are poled by applying an electric field of 1000 kV/cm across the top and bottom electrodes using a direct current (D. C.) voltage source.

[0052] Figure 4 shows a schematic illustration 400 of a high frequency ultrasonic transducer testing setup operating in echo mode. As shown in Figure 4, the high frequency ultrasonic transducer testing setup includes a computer 416, an A/D converter 414, an ultrasonic pulser/receiver 412, the high frequency ultrasonic transducer 418 with one-dimensional piezoelectric nanostructures 104, a water tank 410 (including water 408) and a glass slide 406. The ultrasonic pulser/receiver 412 controlled by the computer 416 generates a voltage pulse, for example with a maximum voltage amplitude of 170 V, for example with pulse width (FWHM) of less than 6.5 ns, to drive the said high frequency ultrasonic transducer 418. The one-dimensional piezoelectric nanostructures 104 in the said high frequency ultrasonic transducer 418 are excited by drive voltage pulse and generate an ultrasonic wave pulse 402 into the surrounding water 408. The ultrasonic wave pulse 402 propagates in the water 408 toward the glass slide 406, which may be 8 mm away from the said high frequency ultrasonic transducer 418 and reflects at the surfaces of the glass slide 406. The reflected ultrasonic wave pulse 404 propagates back to the said high frequency ultrasonic transducer 418 and deforms the one-dimensional piezoelectric nanostructures 104. The deformed one-dimensional piezoelectric nanostructures 104 generate a voltage signal corresponding to that of the (reflected) ultrasonic wave pulse 404. The generated voltage signal is collected by the ultrasonic pulser/receiver 412 and displayed on the computer 416 after having been converted into a digital signal by the A/D converter 414.

[0053] Figure 5A shows a diagram 500 illustrating a time domain signal 506, and Figure 5B shows a diagram 508 illustrating a Fourier spectrum (FFT) 514 of the response of high frequency ultrasonic transducer using P(VDF-TrFE) nanotubes as one-dimensional piezoelectric nanostructures, operating in echo mode, wherein the ultrasonic wave pulse is generated and sensed by the same high frequency ultrasonic transducer with one-dimensional piezoelectric nanostructures, with the distance between the said high frequency ultrasonic transducer and the glass slide target at 8 mm. In Figure 5A, a horizontal axis 502 indicates time, and a vertical axis 504 indicates

voltage. In Figure 5B, a horizontal axis 510 indicates frequency, and a vertical axis 512 indicates magnitude.

[0054] As shown in Figures 5A and 5B, several reflected ultrasonic wave pulses are sensed by the high frequency ultrasonic transducer 418 with the glass slide 406. The first peak (a1) of the time domain signal 506 is the ultrasonic wave pulse reflected from the front surface (facing the high frequency ultrasonic transducer) of the glass slide 406 whereas the second peak (a2) is reflected from the back surface of the glass slide 406. Multiple peaks as observed after the second peak (a2) are the results of internal reflection of ultrasonic wave pulse within the glass slide 406 before reaching back to water 408 and the high frequency ultrasonic transducer 418. The thickness of the glass slide 406 can be calculated based on the time difference between the ultrasonic pulses using the sound velocity in glass slide. The calculated thickness (1.14 mm) using the method according to various embodiments is consistent with the measured value (1.14 mm) using a micrometer. The Fourier spectrum of the ultrasonic wave pulse as shown in Figure 5B indicates that the high frequency ultrasonic transducer 418 has a center frequency of 38 MHz with bandwidth (-6 dB) of 110 %. This demonstrates the broad bandwidth response of the high frequency ultrasonic transducer 418 using one-dimensional piezoelectric nanostructures 104.

[0055] Figure 6 shows a schematic illustration 600 of a high frequency ultrasonic transducer testing setup operating in transmission mode. Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes are used as the one-dimensional piezoelectric nanostructures for a high frequency ultrasonic transducer 604 in transmission mode ultrasonic testing. The high frequency ultrasonic transducer 604 is used to sense the ultrasonic wave pulse generated by the high frequency ultrasonic transducer 602.

[0056] The high frequency ultrasonic transducer 604 using the P(VDF-TrFE) nanotubes may be fabricated with the method as described above. The high frequency ultrasonic transducer 604 using the P(VDF-TrFE) nanotubes is used as sensor, wherein another high frequency immersion ultrasonic transducer 602 with nominal center frequency of 125 MHz is used as a pulser to generate the ultrasonic wave signals. As shown in Figure 6, an ultrasonic wave pulse is generated by the pulser 602 in water and sensed by the high frequency ultrasonic transducer 604 working as sensor with the separation between the pulser 602 and sensor 604 being 12 mm. A commercial ultrasonic transducer with center frequency of 20 MHz may be used as a second sensor for comparison.

[0057] Figure 7A shows a diagram 700 illustrating a time domain signal 706 of the commercial ultrasonic transducer and a time domain signal 708 of the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer 604 according to various embodiments operating in transmission mode according to various embodiments, and Figure 7B shows a diagram 710 illustrating a Fourier spectrum (FFT) 716 of the commercial ultrasonic transducer and a Fourier spectrum (FFT) 718 of the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer 604 according to various embodiments operating in transmission mode. In Figure 7A, a horizontal axis 702 indicates time, and a vertical axis 704 indicates voltage. In Figure 7B, a horizontal axis 712 indicates frequency, and a vertical axis 714 indicates magnitude.

[0058] The time domain signal and Fourier spectrum of the ultrasonic wave pulse as shown in Figure 7 indicate that the high frequency ultrasonic transducer using the P(VDF-TrFE) nanotubes according to various embodiments advantageously has a higher sensitivity and a broader bandwidth (Max voltage of 220 mV with bandwidth of 150 % at -6 dB) as compared to the commercial ultrasonic transducer (Max voltage of 125 mV with bandwidth of 130 % at -6 dB). This demonstrates the potential values of the high frequency ultrasonic transducer using one-dimensional piezoelectric nanostructures for ultrasonic wave sensing, even if the transducers have a significantly simpler structure without any matching layer.

[0059] Vice versa, in another transmission mode operation, the high frequency transducer using the one-dimensional nanostructures according to various embodiments can be used as the pulser for generating the ultrasonic wave, while the another transducer is used as the sensor.

[0060] In a further example, a plurality of poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes with different dimensions (length and diameter) as the one-dimensional piezoelectric nanostructures, are used as ultrasonic sensing and generating element for high frequency ultrasonic transducer. The high frequency ultrasonic transducer is demonstrated for echo mode ultrasonic testing, involving both ultrasonic wave sensing and generating by the same high frequency ultrasonic transducer.

[0061] The one-end sealed ordered anodized alumina membranes with pore size of 300 – 350 nm and two different depths of 4 μm and 2 μm are fabricated by varying the anodization time of the two-step anodization method as described above. The one-end

sealed ordered anodized alumina membrane with pore size of 70 – 100 nm and depth of 1 μm is fabricated using oxalic acid as the anodization agent in the two-step anodization method. The remaining fabrication steps for the high frequency ultrasonic transducer using P(VDF-TrFE) nanotubes may be as described above.

[0062] Figure 8A shows a diagram 800 illustrating time domain signals of ultrasonic transducers using one-dimensional piezoelectric nanostructures with different length (time domain signal 806 for a length of 4 μm , time domain signal 808 for a length of 2 μm , and time domain signal 810 for a length of 1 μm). Figure 8B shows a diagram 812 of Fourier spectra (FFT) of the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer with different lengths and center frequencies operating in echo mode (Fourier spectrum 818 for a length of 4 μm , Fourier spectrum 820 for a length of 2 μm , and Fourier spectrum 822 for a length of 1 μm). In Figure 8A, a horizontal axis 802 indicates time, and a vertical axis 804 indicates voltage. In Figure 8B, a horizontal axis 814 indicates frequency, and a vertical axis 816 indicates magnitude.

[0063] The performances of the ultrasonic transducers are characterized by echo mode ultrasonic testing as described above. The Fourier spectrum of the ultrasonic wave pulse as shown in Figure 8 indicates that the center frequency of the ultrasonic transducer using P(VDF-TrFE) nanotubes increase with shorter length of the nanotubes. The ultrasonic transducer with 1 μm nanotubes achieve the highest center frequency of (or above) 107.5 MHz and bandwidth of 126.5 % (-6 dB). The ultrasonic transducer with such high center frequency and broadband is predicted to achieve resolution of smaller than 10 μm .

[0064] Such a high operating frequency has not been obtained previously using any one-dimensional piezoelectric nanostructures or even any similar structures (including 1-3 composites).

[0065] Advantageously, one-dimensional piezoelectric nanostructures, for example nanotubes, may be used in an ultrasonic transducer with excellent performance, at operating frequency up to higher than 100 MHz, which has not been disclosed with any similar nanostructures previously.

[0066] For example, such an ultrahigh frequency nanotubes ultrasonic transducer (with a frequency of 100 MHz or above) is fabricated by switching the anodization agent (oxalic acid) to produce a much smaller one-dimensional nanostructures (for example four times smaller in diameter and length).

[0067] Figure 8C shows an illustration 824 of a theoretical resolution against the center frequency of the ultrasonic transducer, wherein a horizontal axis 826 indicates center frequency, and a vertical axis 828 indicates a resolution. For illustrative purposes, an arteriole 832, a venule 834, and a capillary 836 are shown.

[0068] Figure 9A and Figure 9B show schematic illustrations of a linear array of high frequency ultrasonic transducers. Figure 9A shows a top view 900, and Figure 9B shows a cross section side view 910. Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes 904 may be used as the one-dimensional piezoelectric nanostructures to produce linear array of high frequency ultrasonic transducers. The one-dimensional P(VDF-TrFE) nanotubes 904 may be fabricated with the method described above. The top electrodes 902 are patterned and separated into multiple electrodes on the P(VDF-TrFE) nanotubes 904 by photolithography, each top electrode for one transducer serving as a single element in the linear array of transducers. The multiple individual top electrodes are connected to an external signal processing unit 908 using a plurality of electrical connections 906, in which the external signal processing unit 908 includes a plurality of independent channels to process ultrasonic wave signals from individual transducers of the array separately. A residue film 912 and bottom electrodes 914, similar to the residue film and the bottom electrodes described above, are illustrated in Figure 9B.

[0069] Figure 10 shows a top view of a schematic illustration 1000 of a two-dimensional array of high frequency ultrasonic transducers. Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes 1004 may be used as the one-dimensional piezoelectric nanostructures to produce a two-dimensional array of high frequency ultrasonic transducers. The one-dimensional P(VDF-TrFE) nanotubes 1004 may be fabricated with the method as described above. Top gold electrodes 1002 may be patterned and separated into multiple electrodes on the P(VDF-TrFE) nanotubes 1004 by photolithography, each top electrode for one transducer serving as a single element in the two-dimensional array of transducers. The multiple individual top electrodes 1002 are connected to an external signal processing unit 1008 via a plurality of electrical connections 1006. The external signal processing unit 1008 may include a plurality of independent channels to process ultrasonic wave signals from individual transducers of the array of transducers separately.

[0070] The high frequency ultrasonic transducer using one-dimensional piezoelectric nanostructures can be used for photoacoustic imaging. Figure 11 shows a schematic

illustration 1100 of a high frequency photoacoustic imaging testing setup. Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes are used as the one-dimensional piezoelectric nanostructures for a high frequency ultrasonic transducer 1108 in photoacoustic imaging. The high frequency ultrasonic transducer 1108 is used to sense the ultrasonic wave pulse generated by laser pulses, which is generated by a laser source 1110.

[0071] The high frequency ultrasonic transducer 1108 using P(VDF-TrFE) nanotubes may be fabricated with the method as described above. The high frequency ultrasonic transducer 1108 using P(VDF-TrFE) nanotubes is used as sensor, wherein hairs 1112 are used as the ultrasonic wave source when the hairs 1112 are illuminated by the laser pulses. For example, four strands of hair 1112 are used as the ultrasonic wave source and the high frequency ultrasonic transducer 1108 mechanically scans through (using a scanning movement) the hairs 1112 to obtain a cross section image of the hairs 1112 through post-reconstruction. The laser source 1110 may have a wavelength of 750 nm, and a duration of 6 ns may be used to illuminate the samples (strands of hair 1112) to produce ultrasonic pulses. A computer 1106, an A/D converter 1102 and an ultrasonic pulser 1104 may be used to obtain the sensing data.

[0072] Figure 12A shows a diagram 1200 of a time domain signal of the commercial transducer (signal 1206) and P(VDF-TrFE) nanotubes high frequency ultrasonic transducer (signal 1208) operating in photoacoustic sensing mode. Figure 12B shows a diagram 1210 illustrating Fourier spectra of the signals shown in Figure 12A (Fourier spectrum 1216 for the commercial transducer and Fourier spectrum 1218 for the P(VDF-TrFE) nanotubes high frequency ultrasonic transducer). In Figure 12A, a horizontal axis 1202 indicates time, and a vertical axis 1204 indicates voltage. In Figure 12B, a horizontal axis 1212 indicates frequency, and a vertical axis 1214 indicates magnitude.

[0073] Figure 12A shows that the high frequency ultrasonic transducer using P(VDF-TrFE) nanotubes has higher sensitivity than a control transducer (commercial transducer) in photoacoustic sensing mode. The photoacoustic image 1220 obtained by the P(VDF-TrFE) nanotube high frequency ultrasonic transducer as shown in Figure 12C shows four strands of hair 1222 with offset in vertical position corresponding to the actual position of hairs. This demonstrates that the P(VDF-TrFE) nanotube high frequency ultrasonic transducer is capable of performing photoacoustic imaging with features as small as 70 μm .

[0074] In another example, poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) nanotubes are used as the one-dimensional piezoelectric nanostructures for making a focused high frequency ultrasonic transducer in scanning ultrasonic microscopy. The focused high frequency ultrasonic transducer is produced by forming the P(VDF-TrFE) nanotubes on a curved anodized alumina membrane as template. One-end sealed ordered anodized alumina membrane is formed on a curved high purity Al foil with the two-step anodization method as described above. The curvature of the ordered anodized alumina membrane defines the focus length of the focused ultrasonic transducer. The remaining fabrication steps for the high frequency ultrasonic transducer using P(VDF-TrFE) nanotubes may be the same as described above.

[0075] A focused P(VDF-TrFE) nanotubes ultrasonic transducer with focal length of 5 mm and center frequency at 107 MHz may be used. Scanning ultrasonic microscopy is performed by mechanically scanning the sample using the focused P(VDF-TrFE) nanotubes ultrasonic transducer operating in echo mode. The scanning speed for the ultrasonic imaging is 5 mm/min, with acquisition frequency of 40 Hz; hence the step size is approximately 2 μm . The samples include copper wires with diameter of about 20 μm . A commercial focused ultrasonic transducer with nominal center frequency of 120 MHz is used as comparison. Real time envelope detection is performed on the obtained radio frequency signal for the formation of the ultrasonic images.

[0076] Figure 13A and 13B show area scan images of the copper wires using a commercial focused ultrasonic transducer (illustration 1300 of Figure 13A) and using the focused P(VDF-TrFE) nanotubes ultrasonic transducer according to an embodiment (illustration 1304 of Figure 13B).

[0077] The cross-section analysis of the images (dotted lines 1302 in Figure 13A and 1306 in Figure 13B) demonstrates the lateral resolution of the commercial focused ultrasonic transducer (in diagram 1308 of Figure 13C) and the focused P(VDF-TrFE) nanotubes ultrasonic transducer according to the embodiment (in diagram 1316 of Figure 13D).

[0078] Curve 1322 of Figure 13D shows that the focused P(VDF-TrFE) nanotubes ultrasonic transducer demonstrated a lateral resolution of 20 μm (full-width at half maximum, FWHM), higher than the commercial ultrasonic transducer of 50 μm as shown by curve 1314 of Figure 13C. In Figures 13C and 13D, horizontal axes 1310 and 1318 indicate lateral distance, and vertical axes 1312 and 1326 indicate intensity.

[0079] Figure 14 shows an illustration 1400 of a scanning ultrasonic imaging setup as another example using a focused P(VDF-TrFE) nanotubes ultrasonic transducer 1402 (center frequency at 40 MHz), which is fabricated by a curved anodized alumina membrane, and which may operate in echo mode and generate an image 1416 of the features under an optically opaque object, through mechanical scanning. The focused P(VDF-TrFE) nanotubes ultrasonic transducer 1402 may include nanotubes 1410 formed on a curved anodized alumina membrane. A scanning movement direction 1404 and a focused ultrasonic wave 1406 are illustrated. A steel plate 1408 with pores 1414 of diameter about 180 μm and covered by adhesive tape 1412 is provided as the imaging target, as shown in the photograph 1418. The area scan image 1416 of the steel plate 1408 is also shown in Figure 14.

[0080] Figure 15 shows an illustration 1500 of a method for producing an ultrasonic transducer. At 1502, a plurality of piezoelectric nanostructures is formed using a template based method, each piezoelectric nanostructure having a diameter of less than 500 nm, and a length of at least twice the diameter, preferably 5 times of the diameter. At 1504, a first electrode coupled to respective first ends of the plurality of piezoelectric nanostructures is provided. At 1506, a second electrode is provided, wherein respective second ends of the plurality of piezoelectric nanostructures are coupled to the second electrode. The method may further include forming an epoxy backing on the first electrode and/ or providing a watertight housing to enclose the backing and first electrode.

[0081] Furthermore, the method may include providing a flat or curved ordered anodized alumina membrane as the template for the forming of the plurality of piezoelectric nanostructures and/ or partially etching the ordered anodized alumina membrane to expose the plurality of piezoelectric nanostructures and to leave the remaining ordered anodized alumina membrane filling the gaps between the piezoelectric nanostructures of the plurality of piezoelectric nanostructures.

[0082] The plurality of piezoelectric nanostructures may be formed by at least one of melt-filling of piezoelectric polymers into pores of the ordered anodized alumina membrane or solution-filling of piezoelectric polymers into the pores of the ordered anodized alumina membrane. The plurality of piezoelectric nanostructures may be nanotubes made of piezoelectric polymers. The piezoelectric polymers may include at

least one of poly(vinylidene fluoride), PVDF or poly(vinylidene fluoride trifluoroethylene), P(VDF-TrFE).

[0083] The superior performance of the high frequency ultrasonic transducers made of the one-dimensional nanostructures as demonstrated above is due to significantly improved piezoelectric performance properties in the one-dimensional nanostructures in comparison with monolithic counterpart, such as larger effective strain piezoelectric constant (d_{33e}) and/or larger effective piezoelectric voltage constant (g_{33e}). Apart from the enhanced piezoelectric material performance, the one-dimensional piezoelectric nanostructures have the desired mechanical impedance match for improved acoustic transmission. For example, the P(VDF-TrFE) polymer nanotubes have lower acoustic impedance (Z : ~ 2.8 Mrayl) than the bulk or film polymer counterpart. The lower acoustic impedance of the nanotubes indicates a better acoustic impedance match with water or human tissue (Z : ~ 1.5 to 2 Mrayl), which favors improved transmission (T) of ultrasonic wave and higher sensitivity of the ultrasonic transducer.

[0084] In accordance with an embodiment, a high frequency ultrasonic transducer (>20 MHz) includes a plurality of vertically aligned one-dimensional piezoelectric nanostructures. The individual one-dimensional piezoelectric nanostructures advantageously have an outer diameter (cylindrical) or width (rectangular) of less than 500 nm and an aspect ratio (length-to-diameter) more than 2, preferably more than 5. Electrodes are formed on both ends of the said one-dimensional piezoelectric nanostructures and connected to a housing for effective electrical connection with external devices. A backing is formed on one end of the said piezoelectric nanostructures array for structural support, ultrasound damping and electrical insulation. A watertight housing encloses the backing for water proofing.

[0085] In accordance with an embodiment, a high frequency ultrasonic transducer advantageously includes a large area of multiple vertically aligned one-dimensional piezoelectric nanostructures.

[0086] Transducers in accordance with an embodiment advantageously are able to operate at frequency significantly higher (up to 100 MHz and even higher) for high resolution ultrasonic imaging, and provide improved performance (higher sensitivity and wider bandwidth) over conventional ultrasonic transducers, as well as a simpler ultrasonic transducer design, without acoustic impedance matching layer needed.

[0087] Applications of transducers in accordance with embodiments include, but are not limited to, high resolution real-time in-vivo biomedical ultrasonic imaging, ultrasonic sensors for high resolution photoacoustic imaging (which is an emerging technology), ultrasonic microscopy for in-vitro biomedical ultrasonic imaging, and advanced high performance non-destructive testing (NDT) (for example in aerospace, semiconductors, automobiles, infrastructures, and industrial equipment.).

[0088] The one-dimensional piezoelectric nanostructures may convert the incident ultrasonic wave into electrical signal for ultrasonic wave sensing and/or convert the applied voltage into ultrasonic wave for ultrasonic wave generation.

[0089] The high frequency ultrasonic transducer may generate and sense ultrasonic wave in echo mode. The high frequency ultrasonic transducer may generate or sense ultrasonic wave in transmission mode including excited by light.

[0090] The one-dimensional piezoelectric nanostructures may be made of piezoelectric polymers, which include but not limited to poly(vinylidene fluoride) (PVDF), poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)).

[0091] The one-dimensional piezoelectric nanostructures may be formed by template based methods using ordered anodized alumina membrane. The one-dimensional piezoelectric nanostructures may be formed by melt-filling or solution-filling of piezoelectric polymers into the pores of said ordered anodized alumina membrane.

[0092] The ordered anodized alumina membrane may be partially etched to expose the one-dimensional piezoelectric nanostructures with the remaining ordered anodized alumina membrane filling the gaps between the one-dimensional piezoelectric nanostructures.

[0093] The one-dimensional piezoelectric nanostructures may be separated from each other by gaps no more than the lateral dimensions of the one-dimensional piezoelectric nanostructures.

[0094] The electric polarization of one-dimensional piezoelectric nanostructures may be aligned in one direction along the long axis of the individual one-dimensional piezoelectric nanostructures.

[0095] The one-dimensional piezoelectric nanostructures may include hollow one-dimensional piezoelectric nanostructures, such as nanotubes, or solid one-dimensional piezoelectric nanostructures, such as nanorods.

[0096] A plurality of one-dimensional piezoelectric nanostructures may be vertically aligned and formed on a curved membrane to produce a focused high frequency ultrasonic transducer with focal length equal to the radius of the curvature of the membrane.

[0097] In accordance with an embodiment, a linear array of high frequency ultrasonic transducers for sensing and/or generating ultrasonic wave may be provided, each using the one-dimensional piezoelectric nanostructures as described above.

[0098] In accordance with an embodiment, a two-dimensional array of high frequency ultrasonic transducers for sensing and/or generating ultrasonic wave may be provided, each using the one-dimensional piezoelectric nanostructures as described above.

[0099] In accordance with an embodiment, a high frequency ultrasonic transducer for sensing and/or generating ultrasonic wave with frequency up to 100 MHz or higher may be provided.

[00100] In accordance with an embodiment, a high frequency ultrasonic transducer for sensing and/or generating ultrasonic wave may be provided, such as for biomedical imaging and non-destructive testing, using one-dimensional piezoelectric nanostructures, including the following: A high frequency ultrasonic transducer for sensing and/or generating ultrasonic wave including an assembly including a plurality of vertically aligned one-dimensional piezoelectric nanostructures, wherein the individual one-dimensional piezoelectric nanostructures have outer diameter (cylindrical) or width (rectangular) less than 500 nm and aspect ratio (length-to-diameter) more than 2, electrodes formed on both ends of the said one-dimensional piezoelectric nanostructures, an epoxy backing formed on one end of the said piezoelectric nanostructures array, and a watertight housing enclosing the backing.

[00101] The high frequency ultrasonic transducer generates or senses ultrasonic wave in transmission mode.

[00102] In accordance with an embodiment, a high frequency ultrasonic transducer with a center frequency higher than 20 MHz, or even higher than 100 MHz, may be provided, with bandwidth up to 126.5 % (-6 dB).

[00103] In accordance with an embodiment, high frequency ultrasonic imaging and high resolution photoacoustic imaging using the transducers, where the ultrasonic wave is excited by light, may be provided.

[00104] Various features are described for a device, but may analogously also be provided for a method (for example a method of operating or using the device, or a method of manufacturing the device), and vice versa.

[00105] Thus, it can be seen that transducers are provided which overcome the problems of low bandwidth and low resolution, and that transducers with high bandwidth and high resolution are provided. Such a transducer may be an ultrasonic transducer including: a first electrode; a second electrode; and a plurality of piezoelectric nanostructures, each piezoelectric nanostructure having a first end coupled to the first electrode, a second end coupled to the second electrode, a diameter of less than 500 nm, and a length of at least twice the diameter.

[00106] The piezoelectric nanostructures may include one-dimensional piezoelectric nanostructures. The one-dimensional piezoelectric nanostructures are configured to convert the incident ultrasonic wave into electrical signal for ultrasonic wave sensing. This may advantageously allow using the transducer as a sensor with high bandwidth and high resolution.

[00107] The one-dimensional piezoelectric nanostructures may be configured to convert the applied voltage into ultrasonic wave for ultrasonic wave generation. This may allow using the transducer as an emitter.

[00108] The ultrasonic transducer may further include a backing formed on the first electrode, which may advantageously increase stability. The ultrasonic transducer may further include a watertight housing enclosing the backing and the first electrode, which may advantageously increase robustness.

[00109] The ultrasonic transducer may be configured to sense ultrasonic waves with a center frequency of at least 20 MHz. The ultrasonic transducer may be

configured to generate ultrasonic waves with a center frequency of at least 20 MHz. This may advantageously provide a high resolution of the transducer.

[00110] The plurality of piezoelectric nanostructures may be aligned at least substantially in parallel. The first electrode and the second electrode may be aligned at least substantially in parallel. This may advantageously provide for a high sensitivity of the transducer.

[00111] Each piezoelectric nanostructure may include a hollow cylinder with at least one closed end. The first electrode may be at least substantially perpendicular to the respective length of each piezoelectric nanostructure; and the second electrode may be at least substantially perpendicular to the respective length of each piezoelectric nanostructure.

[00112] The ultrasonic transducer may be configured to sense ultrasonic waves with a center frequency of at least 100 MHz. The ultrasonic transducer may be configured to generate ultrasonic waves with a center frequency of at least 100 MHz. This may provide a high resolution of the transducer.

[00113] The plurality of piezoelectric nanostructures may be separated from each other by gaps no more than the respective diameter of the piezoelectric nanostructures. This may provide a homogenous imaging quality of the transducer.

[00114] The electric polarization of each piezoelectric nanostructure may be aligned in one direction along the respective length of the piezoelectric nanostructure. This may provide a higher sensitivity of the transducer.

[00115] The plurality of piezoelectric nanostructures may be vertically aligned and formed on a curved membrane to form a focused ultrasonic transducer with a focal length at least substantially equal to the radius of the curvature of the membrane. This may provide a focused transducer.

[00116] The first electrode may include a plurality of top electrodes, and the second electrode may include a plurality of bottom electrodes. Each piezoelectric nanostructure may be coupled to a respective top electrode and to a respective bottom electrode. This may provide an array of the transducers.

[00117] The ultrasonic transducer may be configured to at least one of functions to sense an ultrasonic wave excited by light or to generate an ultrasonic wave in at least one of echo mode or transmission mode.

[00118] In accordance with an embodiment, a linear array of high frequency ultrasonic transducers, including a plurality of ultrasonic transducers as described above, may be provided. This may provide a fast two-dimensional imaging coverage.

[00119] In accordance with an embodiment, a two-dimensional array of high frequency ultrasonic transducers, including a plurality of ultrasonic transducers as described above, may be provided. This may provide a transducer for fast three-dimensional imaging coverage.

[00120] It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. An ultrasonic transducer comprising:
a first electrode;
a second electrode; and
a plurality of piezoelectric nanostructures, each of the plurality of piezoelectric nanostructures having a first end coupled to the first electrode, a second end coupled to the second electrode, a diameter of less than 500 nm, and a length of at least twice the diameter and less than 4 μm ,
wherein the ultrasonic transducer is configured to sense an ultrasonic wave of at least 20 MHz by converting the ultrasonic wave of at least 20 MHz into an electrical signal, and/or to generate an ultrasonic wave having a center frequency of at least 20 MHz by converting an applied electrical signal into the ultrasonic wave having a center frequency of at least 20 MHz.
2. The ultrasonic transducer of claim 1,
wherein the plurality of piezoelectric nanostructures comprise one-dimensional piezoelectric nanostructures.
3. The ultrasonic transducer of any one of claims 1 to 2, further comprising:
a backing formed on the first electrode.
4. The ultrasonic transducer of claim 3, further comprising:
a watertight housing enclosing the backing and the first electrode.
5. The ultrasonic transducer of any one of claims 1 to 4,
wherein each of the plurality of piezoelectric nanostructures has a length of 1 μm or less, and wherein the ultrasonic transducer is configured to sense and/or generate ultrasonic waves with a center frequency of at least 100 MHz.
6. The ultrasonic transducer of any one of claims 1 to 5,
wherein the plurality of piezoelectric nanostructures are aligned at least substantially in parallel.
7. The ultrasonic transducer of any one of claims 1 to 6,

wherein each piezoelectric nanostructure comprises a hollow cylinder with at least one closed end.

8. The ultrasonic transducer of claims 1 to 7,
wherein each piezoelectric nanostructure comprises piezoelectric polymers.
9. The ultrasonic transducer of any one of claims 1 to 8,
wherein the electric polarization of each piezoelectric nanostructure is aligned in one direction along the respective length of the piezoelectric nanostructure.
10. The ultrasonic transducer of any one of claims 1 to 9,
wherein the plurality of piezoelectric nanostructures are vertically aligned and formed on a curved membrane to form a focused ultrasonic transducer with a focal length substantially equal to the radius of the curvature of the membrane.
11. The ultrasonic transducer of any one of claims 1 to 10,
wherein the ultrasonic transducer is configured to sense an ultrasonic wave excited by light or configured to generate an ultrasonic wave in at least one of echo mode or transmission mode.
12. A linear array of high frequency ultrasonic transducers, comprising a plurality of ultrasonic transducers of any one of claims 1 to 11.
13. A two-dimensional array of high frequency ultrasonic transducers, comprising a plurality of ultrasonic transducers of any one of claims 1 to 12.
14. A method for producing an ultrasonic transducer configured to sense an ultrasonic wave of at least 20 MHz and/or generate an ultrasonic wave with a center frequency of at least 20 MHz, the method comprising:
forming a plurality of one-dimensional piezoelectric nanostructures using a template based method, each piezoelectric nanostructure having a diameter of less than 500 nm, and a length of at least twice the diameter and less than 4 μm ,
forming a first electrode coupled to first ends of the plurality of one-dimensional piezoelectric nanostructures; and
providing a second electrode, wherein respective second ends of the plurality of one-dimensional piezoelectric nanostructures are coupled to the second electrode.

15. The method of claim 14, further comprising:
forming an epoxy backing on the first electrode.
16. The method of any one of claims 14 to 15, further comprising:
providing a watertight housing to enclose the backing and the first electrode.
17. The method of any one of claims 14 to 16, further comprising:
providing a flat or curved ordered anodized alumina membrane as a template for
the template based method for the forming of the plurality of one-dimensional
piezoelectric nanostructures.
18. The method of claim 17, further comprising:
partially etching the ordered anodized alumina membrane to expose the plurality
of one-dimensional piezoelectric nanostructures and to leave the remaining ordered
anodized alumina membrane filling the gaps between the piezoelectric nanostructures
of the plurality of one-dimensional piezoelectric nanostructures.
19. The method of any one of claims 17 to 18,
wherein the plurality of one-dimensional piezoelectric nanostructures are formed
by at least one of melt-filling of piezoelectric polymers into pores of the ordered anodized
alumina membrane or solution-filling of piezoelectric polymers into the pores of the
ordered anodized alumina membrane.
20. The method of any one of claims 14 to 19,
wherein the plurality of one-dimensional piezoelectric nanostructures are
nanotubes made of piezoelectric polymers.