



# A Review of UltraHigh Frequency Ultrasonic Transducers

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The ultrahigh-frequency (UHF) ultrasonic transducers are active in various fields, including nondestructive evaluation in the semiconductor industry, microscopic biological organization imaging in biomedicine, particle manipulation, and so on. In these fields ultrahigh-frequency (UHF) ultrasonic transducers play a critical role in the performance of related equipment. This article will focus on the topic of ultrahigh-frequency ultrasonic transducers' preparation, and reviews three aspects: material selection, focus design, and acoustic energy transmission matching. Provides a summary of the current research status, and puts forward some views on the future development of UHF ultrasound devices.

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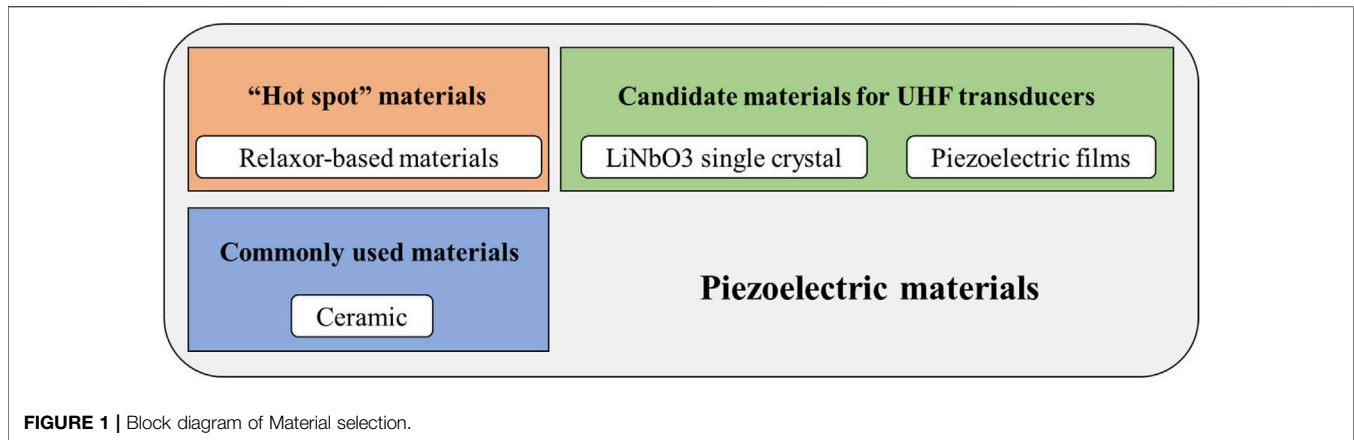
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## INTRODUCTION

As an energy conversion device, the ultrasonic transducer can convert electrical energy into sound energy. Ultrasonic transducers excited by different working frequencies can emit ultrasonic waves of different frequencies. KHz-level ultrasound is generally used for large-scale and long-distance detection, like underwater sonar. In 1–10 MHz, the ultrasonic transducer of this frequency band is usually used in the field of large-size parts non-destructive testing. Up to 100 MHz, medical high-frequency ultrasound is roughly distributed in this frequency range. When it is greater than 100 MHz, it is usually collectively referred to as UHF. The UHF ultrasonic transducer can emit ultra-small wavelength ultrasonic waves because of its extremely high center frequency, which makes it a core component in the high-resolution imaging equipment- Scanning Acoustic Microscope (SAM) (**Supplementary Figure S1**). SAM (Makra et al., 2020) is widely used in non-destructive testing, biological microstructure imaging (Fei et al., 2016; Zhang et al., 2017), and biological cell research (Weiss et al., 2007). Moreover, acoustic tweezers (**Supplementary Figure S1**) based on ultra-high frequency ultrasound transducers (Chen et al., 2017; Lim and Shung, 2017) can be used for the manipulation of very small particles, and have great application value in single-cell research and micro-assembly. Therefore, the preparation of UHF ultrasonic transducers is extremely important.

This article will introduce three important aspects in the preparation process of high-frequency ultrasonic transducers. *Introduction* section introduces different materials for UHF transducer and analysis their advantages and disadvantages. *Material Selection of Ultrasound Generation* section present various transducer focus method and emphasize the difference between the low-frequency lens and high-frequency lens. *Focusing Design of Ultrasonic Emission Energy* section describes the acoustic energy transmission matching problem and mentions a new type of metal-polymer structure matching layer for the UHF ultrasonic transducer.



## MATERIAL SELECTION OF ULTRASOUND GENERATION

### Description of This Section

There are many types of piezoelectric materials. It is necessary to have a general understanding of the existing materials for choosing piezoelectric materials suitable for preparing ultrahigh frequency ultrasonic transducers. As shown in **Figure 1**, this section mainly introduces four types of well-known piezoelectric materials. The first type is piezoelectric ceramics, which have long development history and widespread application in various fields for low-cost, good piezoelectric properties. The second class is relaxor-based materials. Whether ceramic or single crystal is the hot research direction of many materials scholars for the advantages of excellent piezoelectric constant and electromechanical coupling coefficient. The third is single-crystal materials, among which LiNbO<sub>3</sub> have been many successful cases in the preparation of ultra-high frequency ultrasonic transducers. So it is an optional material; the fourth is piezoelectric film. With the development of MEMS technology, its preparation process has become more and more mature. The convenience of piezoelectric materials' thickness control makes it act a key development direction in UHF transducers' preparation in the future. The follow-up of this section will describe the four materials in terms of their applicability in ultra-high frequency ultrasonic transducer devices' preparation.

### Ceramic

Ceramic is a polycrystalline structure composed of many crystal grains of different sizes, and the crystal grains of the same orientation form crystal domains together. Due to the random orientation of the ceramic's crystal domains, from a macroscopic point of view, the ceramic is isotropic, so it was initially considered to have no piezoelectricity, but we can rearrange the crystal domains through polarization to make ceramics piezoelectric. This discovery also led to the rapid development of ceramics in the application of piezoelectric ultrasonic transducers. In 1991, a miniature PZT ceramic high-frequency ultrasonic transducer (20–80 MHz) was reported (Foster et al.,

1991) with a center frequency of 45 MHz and a thickness of 48 μm. The grain size of ceramics (**Supplementary Figure S2**) is usually unevenly distributed in a few microns or tens of microns (Randall et al., 1998; Haertling, 1999; Kong et al., 2000; Pérez et al., 2005; Kamel and de With, 2008; Sangsubun et al., 2008), this is very close to the thickness of piezoelectric materials. In the process of lapping the ceramic material to the specified thickness, as the material thickness gradually approaches the grain size, its mechanical strength will be significantly reduced, and the material will become fragile. The material may fall off in the form of grains resulting in poor material uniformity. The piezoelectric performance of the target material obtained in this way will greatly reduce, and it may even become unpredictable. This is a fatal weakness that prevents them from being used in UHF devices' production.

### Relaxor-Based Materials

Ceramics based on PZT solid solutions have low production costs and good piezoelectric properties. They have been occupying the choice of ultrasonic transducers for many years. Until the emergence of relaxor-based materials, this situation has been broken. Since then, it has been a hot research direction because of their extremely high piezoelectric constant  $d_{33}$  (Park and Shrout, 1997b) and electromechanical coupling coefficient  $k_t$  (Park and Shrout, 1997a). The performance parameters of several materials are shown in **Table 1** (Chen et al., 2014). Due to the similarities in the properties of different materials in this category, only a few representative materials are listed here.

It can be seen from the table that most relaxor-based materials have  $d_{33}$  as high as 2000 or even greater, and the max  $k_t$  is higher

**TABLE 1** | Performance parameters of relaxor-based materials-thickness vibration mode.

	Cut	$d_{33}(\mu\text{C}/\text{N})$	$k_t$	$\epsilon_{33}$
PZN	001	1,100	0.49	3,600
PZN-0.08 PT	001	2070	0.48	4,200
PMN-0.28 PT	001	2,365	0.63	1,032
PIN-0.40PMN-0.33 PT	001	2,742	0.59	659

than 0.60. Piezoelectric performance is excellent, but the speed of sound of this type of material is usually not high, which will cause the thickness of the material to be thinner under the same center frequency requirement. This will greatly increase the difficulty of processing, and even cannot be manufactured. In addition, the high dielectric constant of the relaxor ferroelectric will make the area of the piezoelectric unit that meets the 50-ohm impedance matching too small, which will greatly increase the difficulty of machining and will also affect the ultrasonic emission intensity. Therefore, although the relaxor ferroelectric has excellent piezoelectric properties, it is not a suitable choice for the preparation of ultra-high frequency ultrasonic transducers due to the limitation of other factors.

## LiNbO3 Single Crystal

Since it was invented by Jan Czochralski in 1916 (Uecker, 2014), the growth of bulk single crystals technique (Czochralski Method) has been widely spread and developed, and then the Bridgman method (Chen et al., 2003) using crucibles to prepare single crystals was reported. This method can effectively ensure that the raw material composition ratio is affected by the external environment. Subsequently, based on these two methods, many new preparation methods have been introduced through process improvement. The continuous maturity of single crystal preparation technology has also promoted the research and development of single crystals.

Single crystal has a very high piezoelectric constant  $d_{33}$  and electromechanical coupling coefficient  $k_t$ , making it a promising candidate for making high-performance transducers. Moreover, unlike polycrystalline ferroelectric ceramics, single crystals are not limited by factors such as crystal grains and porosity and have the potential to produce ultra-high frequency transducers. The grown large-size single-crystal generally needs to be cut into the plate, single crystal has a crystallographic axis, and the cutting direction affects the piezoelectric performance of the single crystal. Different device performance requirements corresponding to different cutting types. A plate cut with its surface perpendicular to the  $x$ -axis of a crystal is called  $x$ -cut, and the same as other axes.

LiNbO<sub>3</sub> single crystal with relatively high acoustic velocity, excellent piezoelectric properties, and small dielectric constant, have advantages in manufacture high frequency and large aperture ultrasonic transducers. For better piezoelectric property, we usually choose 36° Y-cut LiNbO<sub>3</sub> as the transducer's piezo layer. The detail parameters include thickness mode electromechanical coupling, dielectric permittivity, longitudinal wave velocity is about 0.49, 39, 7,340 m/s, respectively. To make UHF transducers based on LiNbO<sub>3</sub>, we need to lap it to a few microns, which can be achieved in theory, but the process is quite difficult. To meet the requirements of high-resolution imaging of biological microstructures, Chunlong Fei (Fei et al., 2016) prepared a 100–300 MHz UHF ultrasound transducer. As shown in **Supplementary Figure S3**, you can see on the left that the thickness of the piezoelectric layer of the 300 MHz LN UHF ultrasound transducer is only 9  $\mu\text{m}$ , the UBM ultrasound scan

image of zebrafish eye on the right, the internal structure of the eye can be distinguished.

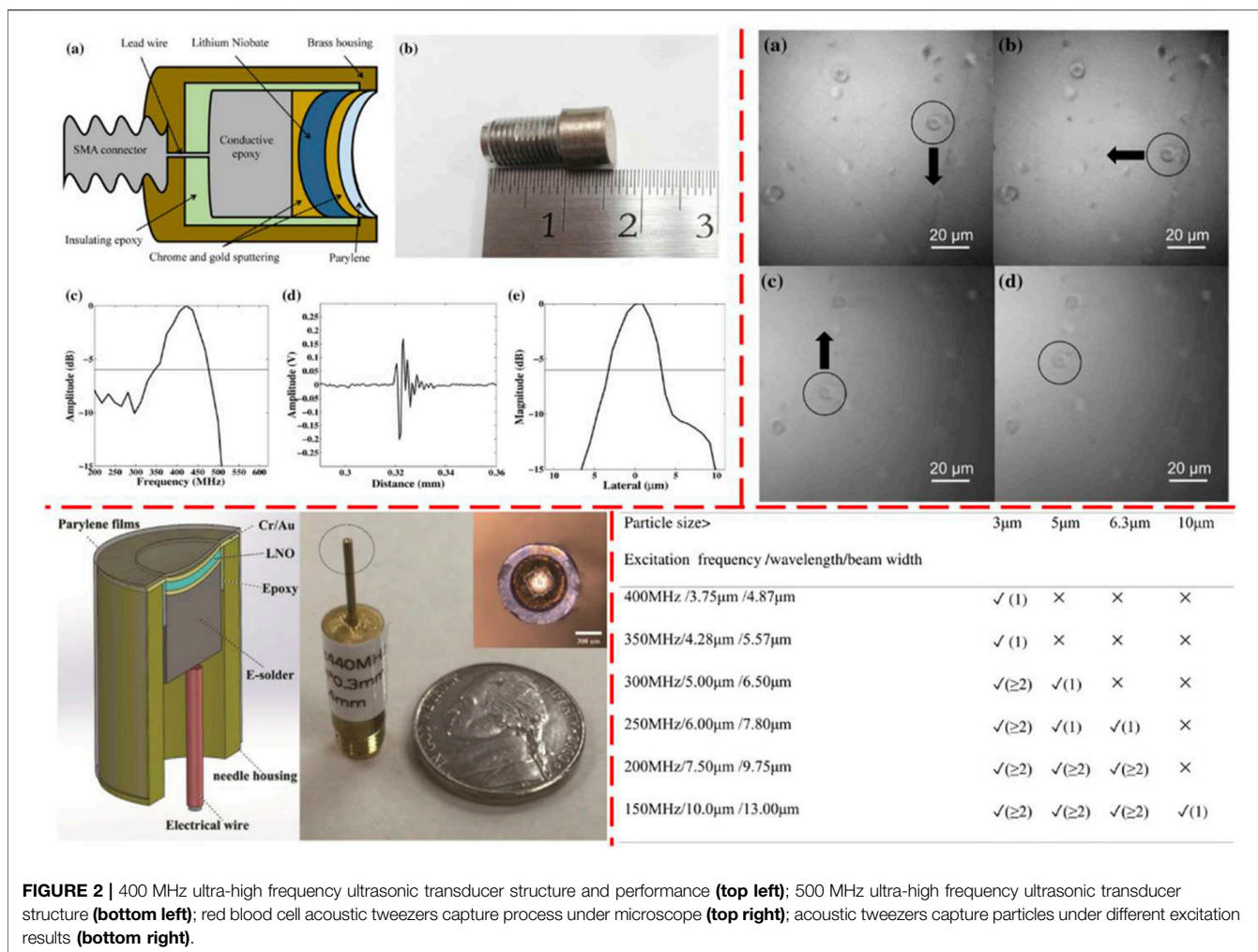
As shown in **Figure 2**, Hae Gyun Lim and K. Kirk Shung (Lim and Shung, 2017) prepared an LN piezoelectric layer with a thickness of 7.1  $\mu\text{m}$  and used a focus design to generate a UHF probe capable of emitting a 6.5  $\mu\text{m}$  width beam. The UHF transducer has a center frequency of up to 400 MHz, which achieves Acoustic tweezers capture a single red blood cell (~7.5  $\mu\text{m}$ ). Xiaoyang Chen (Chen et al., 2017) used a 6  $\mu\text{m}$  thick LN to prepare an ultra-high frequency ultrasonic transducer with a resonant frequency of 526 MHz, and achieved selective acoustic tweezers for particles in the range of 3–10  $\mu\text{m}$  by changing the excitation, as shown in **Figure 2**.

Although there have been reports of the above-mentioned UHF LN single-crystal devices, it is still extremely difficult to control the thickness of LN materials of a few microns. The preparation process requires a lot of time and effort, and with the further increase of the center frequency, the degree of difficulty may be more than a simple linear increase, so to increase the upper limit of UHF ultrasonic transducers, new materials are needed to provide the feasibility of extremely low thickness control.

## Piezoelectric Films

With the development of MEMS technology, piezoelectric film manufacturing technology has also made great progress, which provides a new choice for piezoelectric materials for ultra-high frequency ultrasonic transducers. Films based on traditional ferroelectric materials have excellent piezoelectric properties and mature thickness control technology. So far, many researchers have done a lot of work in this area. As early as 1997, DA Barrow produced a 60  $\mu\text{m}$  thick PZT film through the sol-gel method (Barrow et al., 1997). This method firstly disperses PZT particles into a PZT sol-gel matrix to achieve a 0–3 ceramic/ceramic composite. Then the ceramic/ceramic composite is spin-coated and distributed on the silicon substrate, followed by sintering and annealing, repeat the above steps layer by layer until the specified thickness is reached. As shown in **Supplementary Figure S4**, it is a 20  $\mu\text{m}$  PZT film coated with ten layers. The PZT films prepared by this method have a good piezoelectric constant  $d_{33} = 325 \text{pC/N}$ .

Subsequently, many UHF transducer devices based on PZT films were published. In 2006, P Marechal improved the sol-gel and introduced a vacuum precursor solution filling method to improve the quality of the film. A 13  $\mu\text{m}$  thick PZT film was fabricated on the Pt-substrate, with this film, a 103 MHz ultra-high frequency ultrasonic device was fabricated (Marechal et al., 2006). The pulse-echo test results are shown in the upper part of **Supplementary Figure S5**. The -6 dB bandwidth reaches 70%, and the pulse-echo waveform is also relatively beautiful. Then in 2008, BP Zhu grew PZT films by a ceramic powder/sol-gel solution modified composite method, and prepared a 156 MHz PZT films transducer (Zhu et al., 2008) with a -6 dB bandwidth of 50%, as shown in **Supplementary Figure S5**, the bottom left is the experimental measurement results and the bottom right is the simulation result of PiezoCAD.



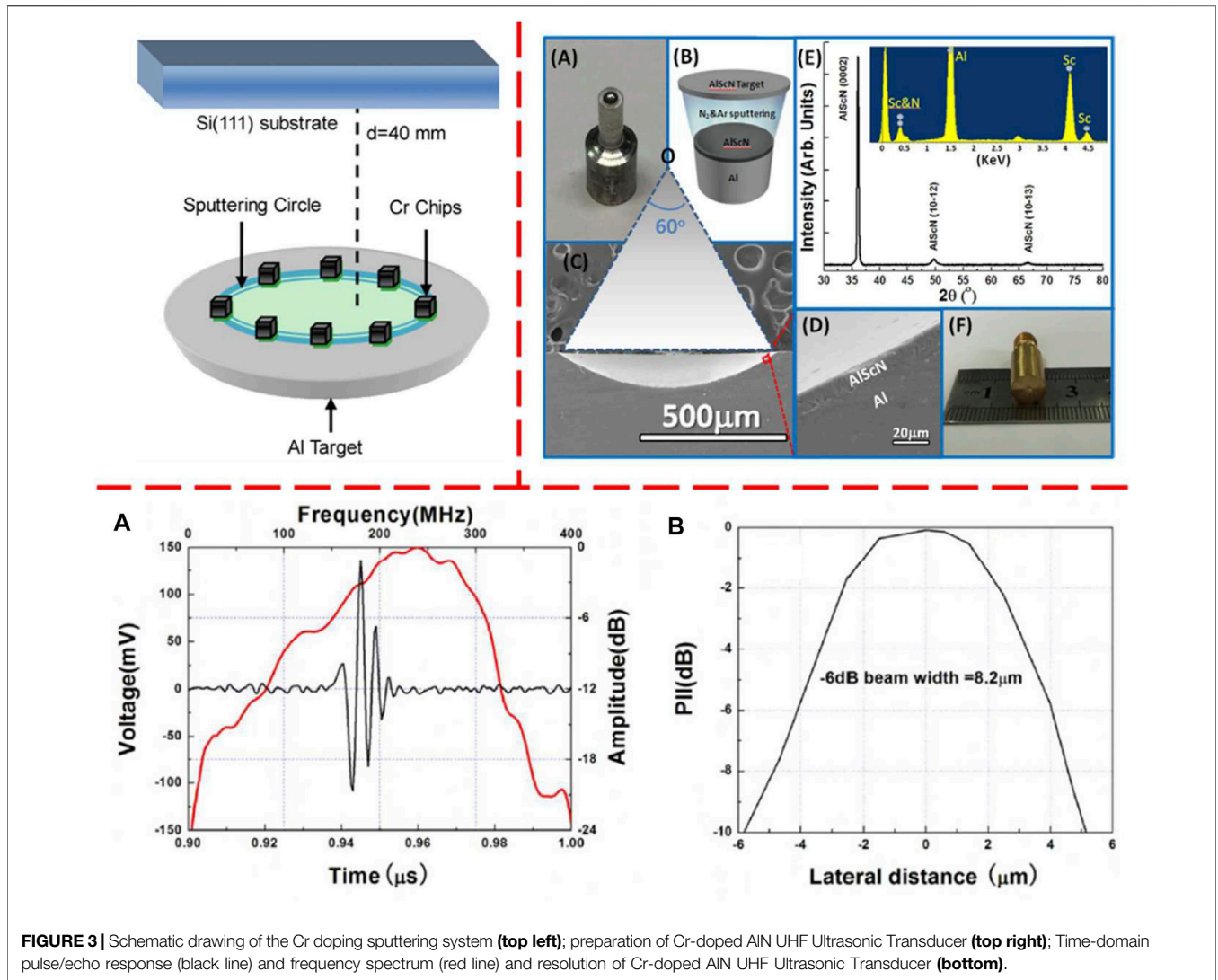
**FIGURE 2 |** 400 MHz ultra-high frequency ultrasonic transducer structure and performance (top left); 500 MHz ultra-high frequency ultrasonic transducer structure (bottom left); red blood cell acoustic tweezers capture process under microscope (top right); acoustic tweezers capture particles under different excitation results (bottom right).

PiezoCAD is a simulation software derived from the KLM model. When the frequency is not particularly high, the simulation results are still relatively close, but when the frequency continues to increase, many factors that are difficult to consider are introduced by high frequency. The aspects involved in the KLM model may not be enough to ensure the accuracy of the simulation. It seems that the deviation is not particularly large here. The simulation results can still play a certain reference role. In the UHF frequency, the results of simulation through finite element calculation, such as PZFlex, COMSOL, and other software, are relatively more reliable, but as the frequency increases, the simulation time will also increase significantly. XY Chen combined composite ceramic sol-gel film technique with sol-infiltration technique and fabricated up to 300 MHz 0–3 composite PZT films transducer (Chen et al., 2016), the center frequency of 300-MHz is the highest value in a PbTiO3 based ceramic ultrasonic transducers ever reported (Supplementary Figure S6).

In consideration of environmental protection, lead-free material films have also been added to the research on the preparation of UHF transducers. ST Lau has done a series of

UHF transducer preparations based on lead-free piezoelectric films, the result shown in Supplementary Figure S7 (Lau S.-t. et al., 2010; Lau S. T. et al., 2010; Lau et al., 2011). K H Lam studied KNN/BNT ultra-high frequency ultrasonic transducer devices in the frequency range of 170–320 MHz. Pulse echo is shown in Supplementary Figure S8 (Lam et al., 2013b).

The traditional bulk piezoelectric relaxor ferroelectric material has attracted the attention of many researchers due to its extremely high piezoelectric constant and dielectric constant. It has also been seen in the application of film materials. PMN-PT film is considered to can replace the PZT film, but its extremely high dielectric constant will make it difficult to control the ultrasonic transducer device during electrical impedance matching. A feasible solution is to use a composite sol-gel method to composite PMN-PT and PZT according to a certain mixing ratio, then made them into xPMN-PT-(1-x)PZT film (Hsu et al., 2012). While retaining high piezoelectric performance, the dielectric constant is adjusted to a controllable range, such as Supplementary Figure S9, on the left is the change in dielectric constant, and on the right is the pulse-echo waveform of an ultra-high frequency transducer made



**FIGURE 3** | Schematic drawing of the Cr doping sputtering system (top left); preparation of Cr-doped AlN UHF Ultrasonic Transducer (top right); Time-domain pulse/echo response (black line) and frequency spectrum (red line) and resolution of Cr-doped AlN UHF Ultrasonic Transducer (bottom).

of 0.9PMN-PT-0.1PZT composite film. In addition to material composition, it is also a commonly used material modification method to change the crystallographic properties and microstructure of materials through particle doping and to change material properties. These two methods can be combined to provide more possibilities for UHF transducer materials. HS Hsu further adjusted the performance of the xPMN-PT-(1-x)PZT composite film through Ag doping (Hsu et al., 2013) and successfully fabricated an ultra-high frequency ultrasonic transducer device. The results are shown in **Supplementary Figure S10**.

The overall performance of the thin film prepared by the traditional ferroelectric materials has declined, but it is still related to the electrical performance of the bulk material. Furthermore, the particle doping and material composite can be used in the thin film, which will improve the performance of the material. However, there are also shortcomings. The high temperature during the film densification and annealing process

cannot be withstood by other materials in the ultrasonic transducer. As a result, the growth of the piezoelectric film is not completely compatible with the manufacturing process of the transducer, and secondary processing operations are usually required for the grown film. It is very difficult to operate a film of several microns, which will greatly affect the repeatability of the preparation of the transducer, the consistency cannot be guaranteed, and the process complexity is high, which is not conducive to mass production.

The semiconductor industry is developing rapidly, and its mature MEMS technology provides a new path to produce UHF transducers. Using ZnO and AlN, which are commonly used in semiconductors, to replace traditional ferroelectric materials to

**TABLE 2** | Material parameters of transducer design.

Dielectric properties	Piezoelectric properties	Acoustic properties
$C = \frac{\epsilon_{33}A}{t}$	$k_t^2 = \frac{e_{33}^2}{C_{33}\epsilon_{33}}, d_{33}$	$Z_P = \rho C_m, f = n \frac{C_m}{2t}$

**TABLE 3 |** Material analysis summary.

	Advantage	Shortcoming	UHF devices applicability
Ceramic	Low cost, complete variety, good piezoelectric performance	Grain size limitation	No, the material has limitations
Relaxor-based materials	Excellent piezoelectric performance	Large dielectric constant makes impedance (50 Ω) matching difficult, sound velocity is not large enough	No it's difficult to fabricate
LiNbO3 single crystal	Good piezoelectric performance, large sound velocity, no grain size limitation, small dielectric constant	Difficult to realize precise thickness control	Yes, but there is a frequency limit, and it is difficult to reach more higher frequency
Ferroelectric films	Good piezoelectric performance, precise thickness control	Poor compatibility between material growth and transducer preparation	Yes, but manufacturing repeatability needs to be improved
Semiconductor films	Mature technology, precise thickness control	Poor piezoelectric performance	Yes, but material performance needs to be improved

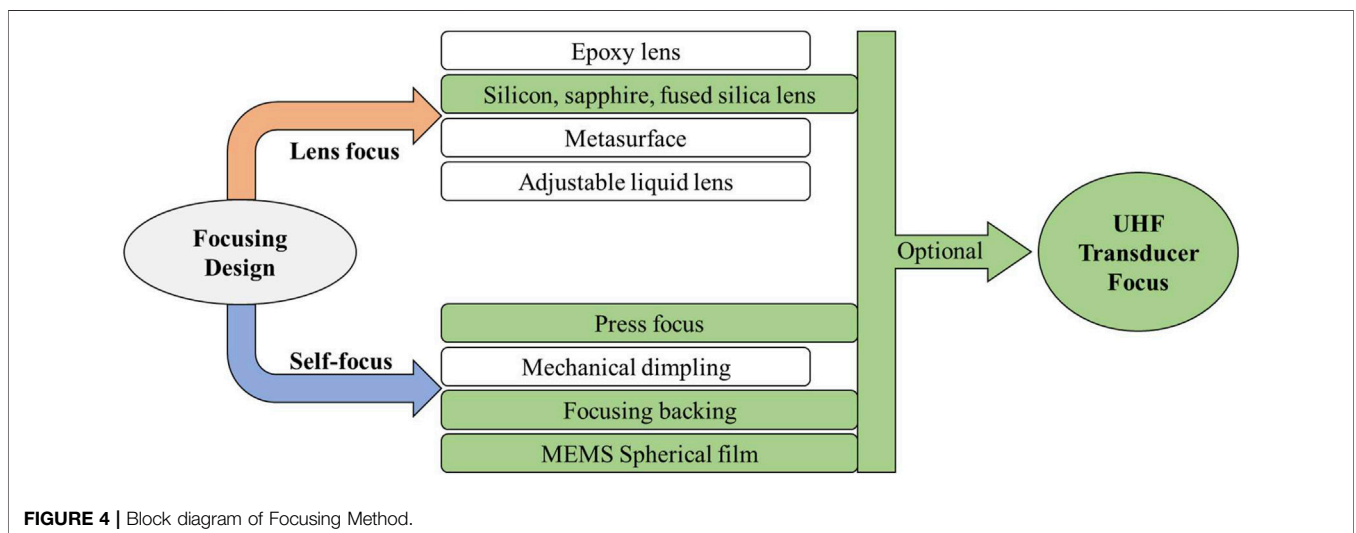
prepare ultra-high frequency ultrasonic transducers, its consistency and reliability will be better in terms of process realization. But in terms of material piezoelectric properties, ZnO and AlN are far inferior to traditional ferroelectric materials. It is also necessary to improve the performance of the material by doping. For example, the piezoelectric constant of AlN piezoelectric film sputtered by Cr doping (Luo et al., 2009) will be improved to a certain extent, as shown in **Figure 3**. E Wistrela also mentioned that XRD and surface topography analysis (Wistrela et al., 2018) can as a straightforward approach to estimate the piezoelectric activity of Cr doped AlN thin films. K San reported a 40–80 MHz Cr-doped AlN ultrasonic transducer (Sano et al., 2018). BP Zhu reported a 200 MHz Cr-doped AlN ultra-high frequency ultrasonic transducer (Zhu et al., 2017), the preparation of the transducer is shown in the upper right of **Figure 3**, the pulse-echo and resolution are shown in **Figure 3** bottom left.

The latest research report that introduces Yb into aluminum nitride (AlN) leads to a large enhancement in the material's piezoelectric response (d33). The maximum d33 is calculated to

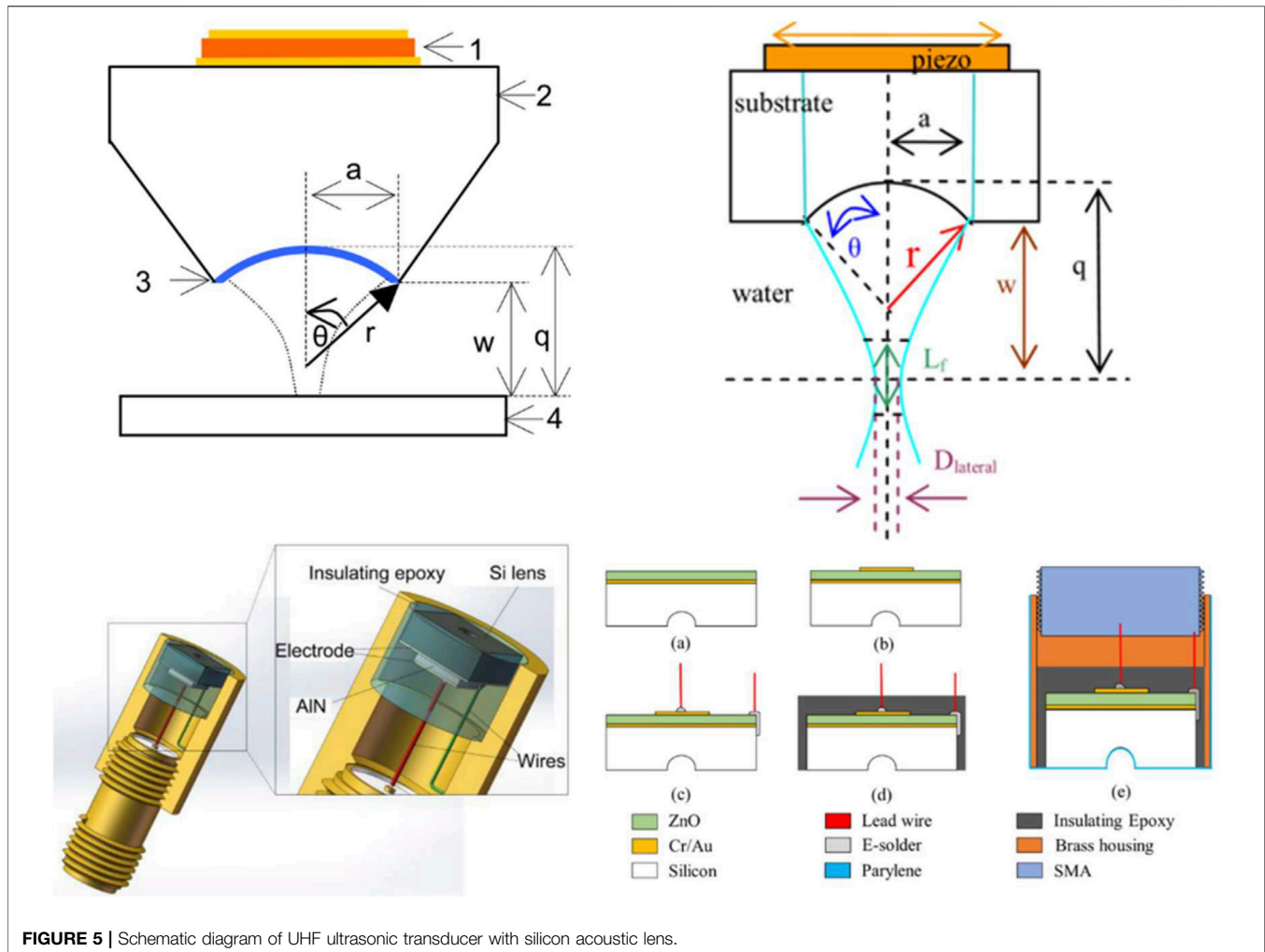
be over 100 pC/N, which is 20 times higher than that of AlN(Hirata et al., 2021). However, there are no reports of successful preparation of devices from related materials.

### Summary of This Section

The selection of piezoelectric materials is the most critical step in the preparation of ultrasonic transducer devices. The choice of materials needs to be considered from two major aspects. One aspect is the process, which determines whether the material can successfully fabricate UHF devices. The thickness of the piezoelectric material is usually half a wavelength at the working frequency. When the working frequency is up to the ultra-high frequency, the thickness control of the piezoelectric material of a few microns is a big problem. Therefore, when selecting the material, it is necessary to consider its growth process, processing difficulty, and whether it can be better compatible with the preparation process of the transducer device to ensure the stability of the preparation process of the transducer. Another aspect is the performance of the material, which determines the final device performance. The parameters



**FIGURE 4 |** Block diagram of Focusing Method.



in the thickness vibration mode are mainly considered here. Generally, the material parameters considered in the preparation of ultrasonic transducers are piezoelectric constant  $d_{33}$ , electromechanical coupling coefficient  $k_t$ , dielectric constant  $\epsilon_{33}$ , acoustic impedance  $Z_p$ , and sound velocity  $c_m$ . Compared with conventional devices, UHF devices pay more attention to the speed of sound and dielectric constant. The former determines the final thickness of the piezoelectric material, and the latter determines the final area size of the piezoelectric material when the electrical impedance is matched to  $50\Omega$ . Reasonable thickness and area size can ensure the success of preparing UHF transducers. Then we need to consider the piezoelectric constant and electromechanical coupling coefficient, which affect the final signal amplitude and energy loss of the device. The material parameters mentioned above are all in **Table 2**, where  $n$  is an odd integer and usually  $n = 1$ , it means the lowest resonant frequency.  $C$  is the clamped capacitance,  $A$  is the area of piezoelectric materials,  $t$  is the thickness of piezoelectric materials,  $e_{33}$  is the piezoelectric stress constant,  $c_{33}$  is the elastic constant,  $c_m$  is the speed of sound inside the piezoelectric material,  $\rho$  is the density.

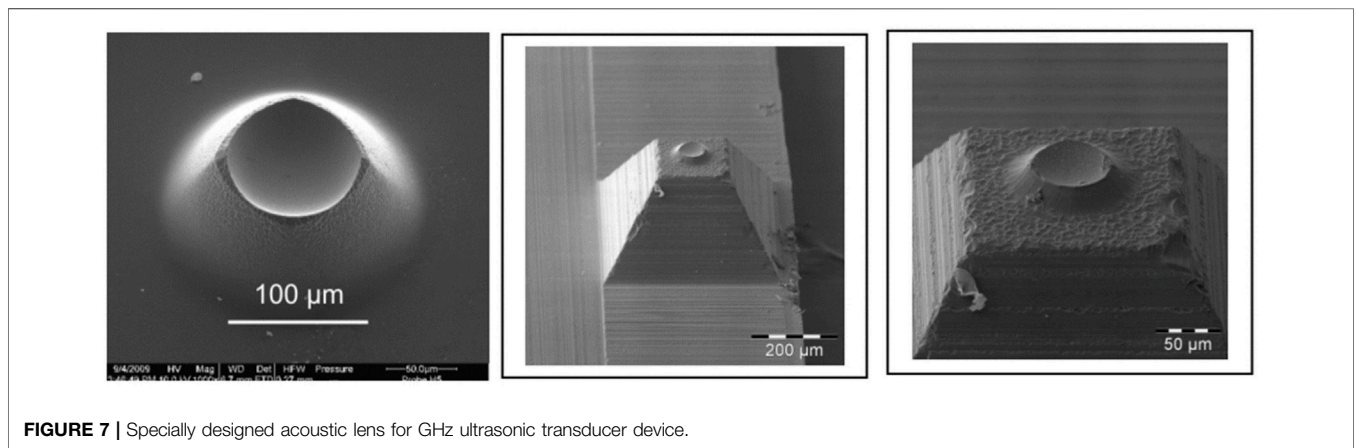
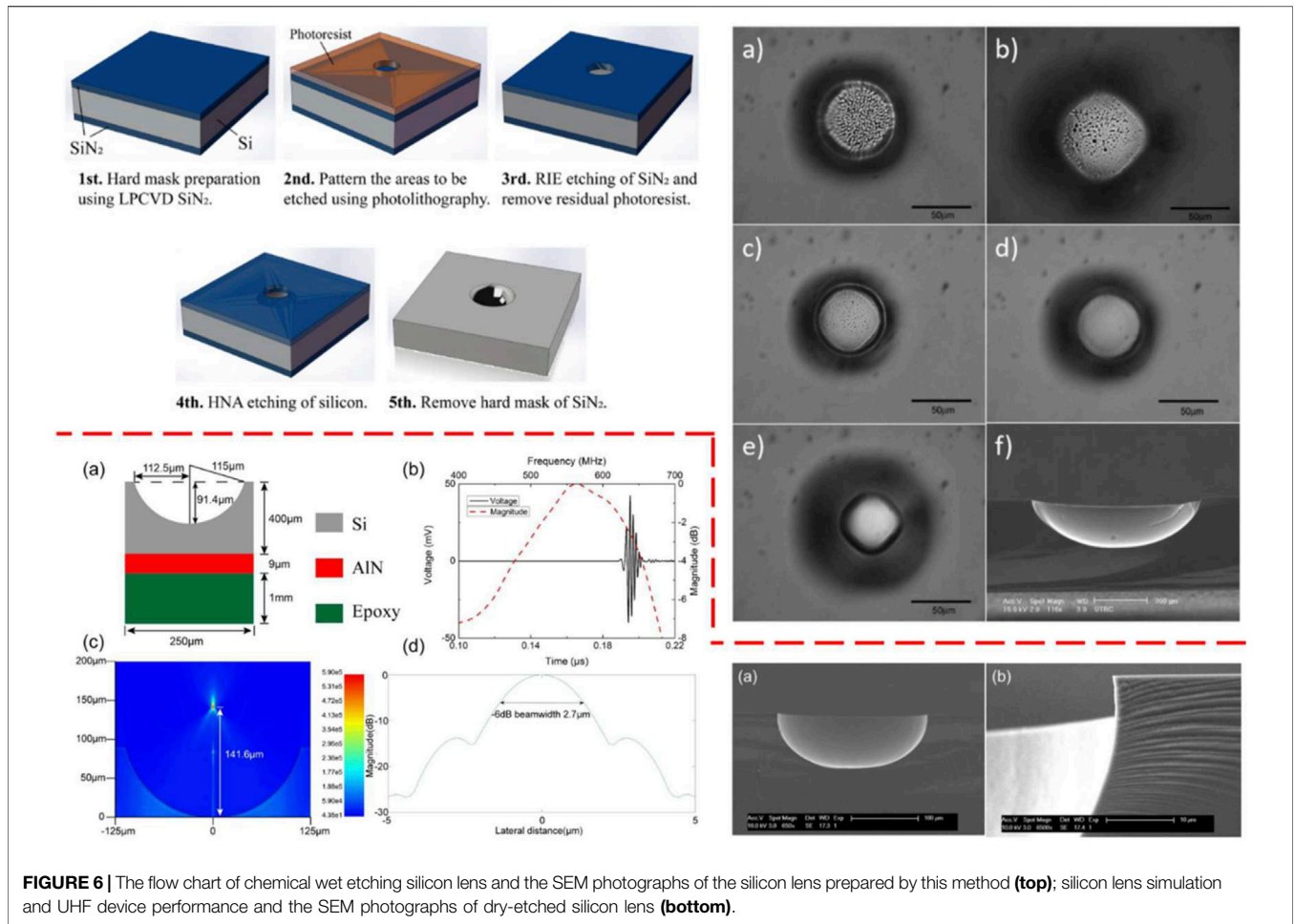
There is no best material, only the most suitable material. **Table 3** analyzes and compares the four types of piezoelectric materials' advantages and disadvantages mentioned, and gives an evaluation of the applicability of these four materials in ultra-high frequency ultrasonic devices' preparation.

## Focusing Design of Ultrasonic Emission Energy

### Description of This Section

The higher the frequency, the greater the attenuation of ultrasonic energy. To concentrate more emitted energy, the focus design of the transducer is usually necessary. Moreover, the UHF device has a higher frequency and smaller thickness, so its focus needs to consider tremendous sound attenuation and difficulty in process realization.

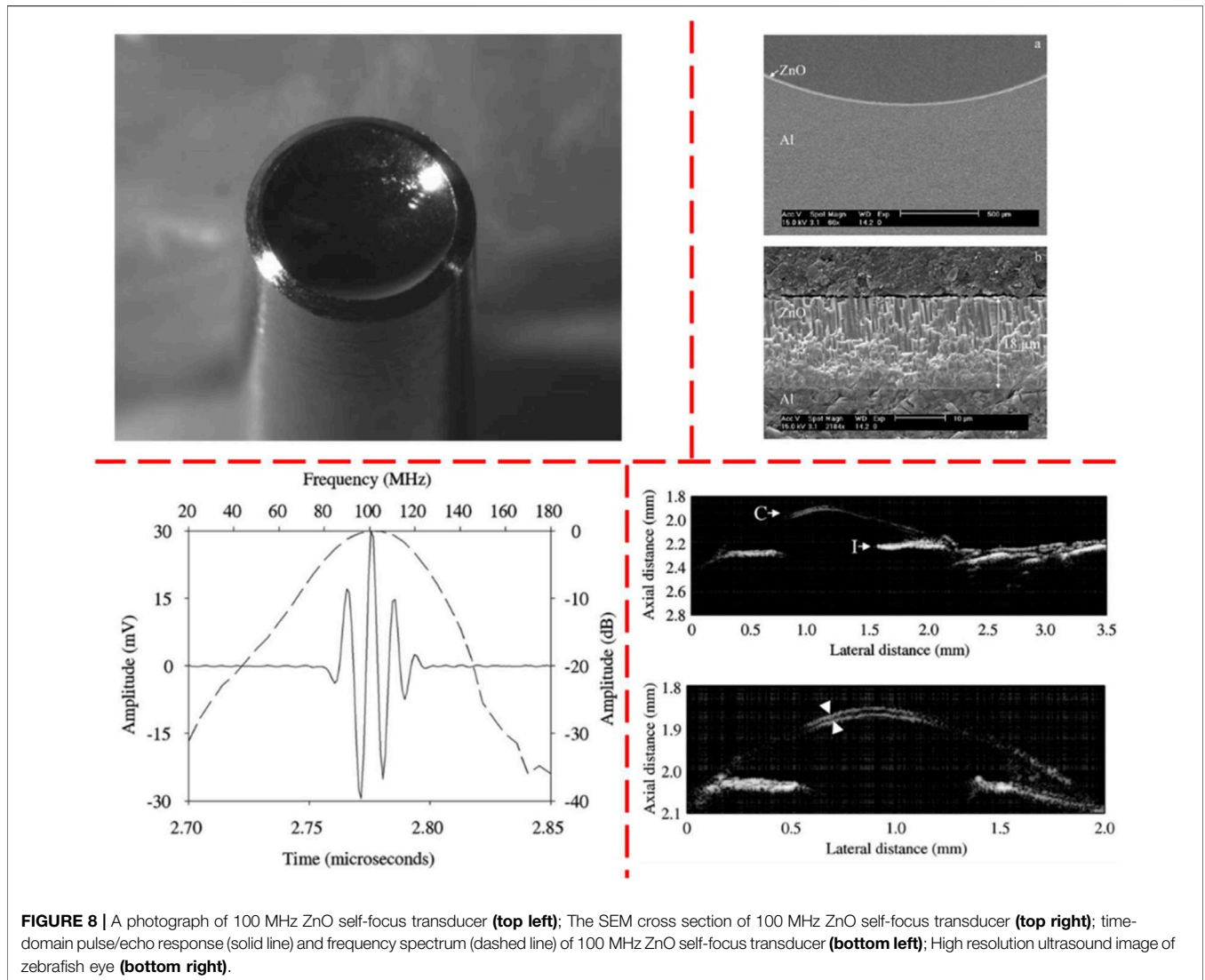
As shown in **Figure 4**, the focus design in this article divides into two directions. One is to achieve focusing by adding a lens to the surface of the piezoelectric material, which includes epoxy lens, metamaterial lens, adjustable liquid lens, Silicon lens, sapphire lens, and fused silica lens. The other is to achieve the



purpose of focusing by changing the shape of the piezoelectric material itself. There present four methods. The first one is to use a small ball to press the piezoelectric material to a focused shape. The second method is to lap the surface of the piezoelectric

material with a mechanical grinding wheel. The third way applies a focused shape backing material. The last one combines MEMS technology to fabricate a focused shape piezoelectric material. Considering the difficulty of the process and the final focusing





effect, the focusing methods adapt to ultra-high frequency ultrasound devices' fabrication have been marked in green in the figure for easy viewing. The following content will illustrate these focusing methods.

### Press Focus

Generally speaking, the most commonly used focusing method is spherical pressure focusing (Fei et al., 2018b), which uses a small ball to press a piezoelectric material to a spherical concave surface through a weight (**Supplementary Figure S11**). This method is simple and the cost is low, but the piezoelectric material in the UHF device is very thin. Using this method will

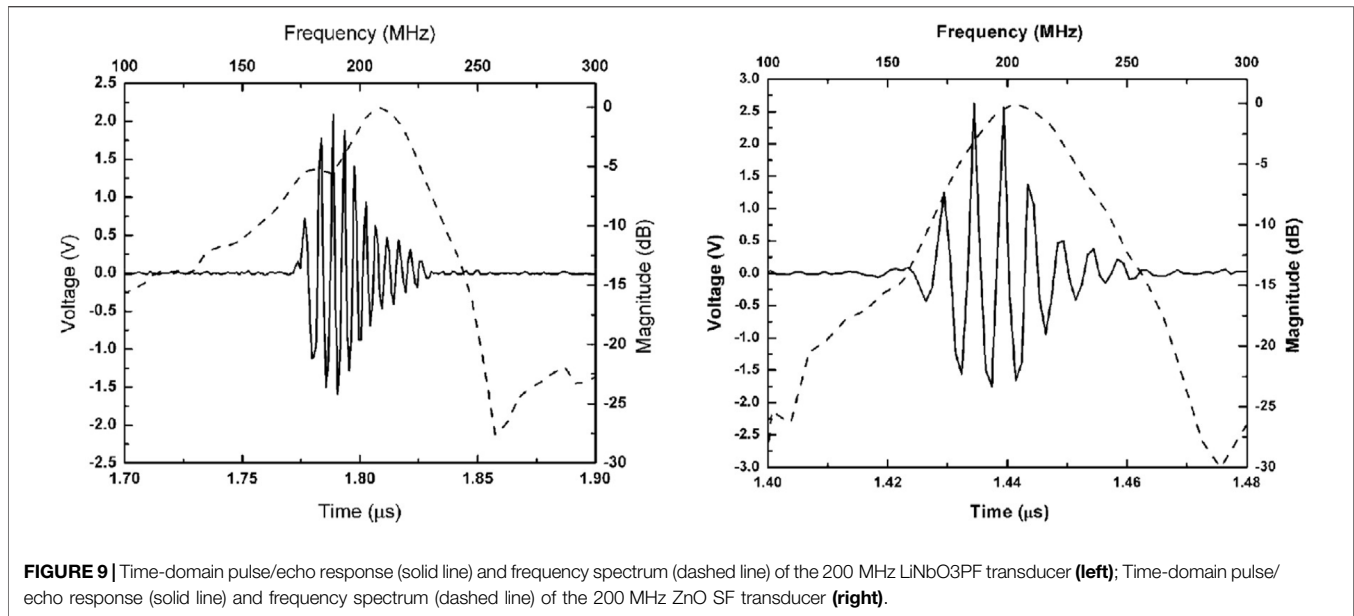
**TABLE 4** | UHF ultrasonic transducer acoustic lens material properties.

	Sapphire	Fused quartz	Si(100)
Acoustic velocity (m/s)	11,100	5,900	8,430
Acoustic impedance ( $10^6 \text{kg/m}^2 \cdot \text{s}$ )	40	15.6	19.8
Loss at 1 GHz (dB/cm)	0.2–0.5	12.1	6.5

often cause the piezoelectric material to break, and finally, make the performance of the device more difficult to predict, and the consistency is difficult Guaranteed. (Cannata et al., 2000).

### Mechanical Dimpling

Another commonly used focus method is mechanical dimpling (Lam et al., 2012; Chen et al., 2013; Fei et al., 2018a). As shown in **Supplementary Figure S12**, the upper left is 5 MHz mechanical focusing PMN-PT single crystal, the top right is the surface morphology of the piezoelectric material after mechanical digging, and the bottom is the production flow chart of the 35 MHz PMN-PT IVUS mechanical focusing transducer. It can be seen in that the mechanical digging is performed on the piezoelectric material through a circular grinding wheel. The surface is made by pressing and polishing, but it is impossible to perform machining on the surface of the piezoelectric material of the ultra-high frequency device of a few microns.



## Acoustic Metasurface

Acoustic metasurface (**Supplementary Figure S13**) is a relatively novel way of sound field control (Al Jahdali and Wu, 2016; Zhu et al., 2016), but its structure usually has a large attenuation. Furthermore, with the frequency increases, the fabrication of metasurface structure is harder to realize, which makes it very difficult to play a role in the range of UHF applications. However, it can play a great role in regulating a specific sound field.

## Adjustable Focus

There is an unconventional, but very interesting lens, as shown in **Supplementary Figure S14**. It can flexibly change the focus point by injecting liquid to control the curvature of the lens (Li et al., 2021b; Li et al., 2021c). It is hard to apply in UHF ultrasonic devices, but some special occasions may play a miraculous effect.

## Silicon Lens

In the low-frequency range, epoxy can be considered to prepare a lens (Cannata et al., 2003), the epoxy lens is easy to mold and the prepared lens surface is smooth. Sapphire, fused quartz, and silicon are usually used in ultrahigh-frequency ultrasonic devices. Acoustic lenses are made by machining or etching firstly, and then ZnO is sputtered on the surface of the lens as piezoelectric materials to make UHF ultrasonic transducers, as shown in **Figure 5** (Kushida et al., 1988; Hashimoto et al., 1991; Vispute et al., 1997; Molarius et al., 2003; Jakob et al., 2009). This production process is relatively reliable and repeatable.

In 2017, CL Fei prepared a silicon lens through chemical wet etching. The preparation process and preparation effect are shown in the upper part of **Figure 6**. By sputtering a ZnO piezoelectric layer on this lens, a 300 MHz UHF device was successfully prepared (Fei et al., 2017). Then D Li and CL Fei reported on the silicon lens prepared by dry etching, and successfully prepared a 500 MHz AlN ultra-high frequency ultrasonic transducer (Li et al., 2018), the performance of the silicon lens and the transducer, as shown in **Figure 6** below.

Jakob mentioned in the article that the shape of the lens in **Figure 7** can not only reduce the interference of the edge echo but also can concentrate more energy in the target imaging area, reducing the divergence of the beam side lobes. This kind of acoustic lens can be applied to the ultrasonic scanning microscope of the GHz level. However, the realization of this kind of lens is more complicated, and the cavity needs to be etched by the wet method, and then the excess part of the edge is removed by the dry method (Jakob et al., 2007; Jakob et al., 2009). Some acoustic lens materials are listed in **Table 4** for reference (Hashimoto et al., 1991).

## Focusing Backing

Since the acoustic lens will introduce a certain amount of attenuation, self-focusing of piezoelectric materials (Zhou et al., 2007; Jakob et al., 2009; Zhu et al., 2017) may be a better method. In this method, a focusing backing substrate is prepared in advance, and then piezoelectric material is sputtered on it, to avoid the attenuation caused by the acoustic lens. But in this way, the choice of the backing base material is more important. If the acoustic impedance of the backing material is too large from the piezoelectric material, the ultrasonic energy propagating after the phase cannot be absorbed, which will result in a larger ring in the echo signal. Al has many advantages, such as good processability, easy to process into spherical focusing grooves, good electrical conductivity, acoustic impedance closer to ZnO compared to other metals, higher melting point, and not being affected by the operating temperature during the preparation of piezoelectric materials. It is suitable to be a base material for self-focusing UHF transducers. JM Cannata fabricated a 100 MHz self-focusing UHF device using Al as the substrate (Cannata et al., 2008) and performed high-resolution imaging of zebrafish eyes (**Figure 8**). KH Lam also chose Al as the substrate. A 200 MHz self-focusing UHF device was fabricated on the substrate (Lam et al., 2013a), and the performance of the LN spherical pressure focusing UHF device was compared at the same

**TABLE 5** | Summary of focusing methods.

	Advantage	Shortcoming	UHF devices applicability
Epoxy lens	Simple molding, low cost	Large attenuation	No
Silicon, sapphire, fused silica lens	Low attenuation, high surface smoothness	Complex process, high cost	Suitable for ultrahigh frequency, recommended method
Metasurface	Design flexibility	Large attenuation, complex process	No
Adjustable liquid lens	Adjustable focus	Not burst enough	No
Process focus	Easy to operate, low cost	Damage to piezoelectric materials, poor consistency	Applicable, but the consistency of equipment performance is difficult to guarantee
Mechanical dimpling	Easy to operate, low cost	Not suitable for microfabrication	No
Focusing backing	Easy to operate, low cost	Relay on machining accuracy	Applicable, there is an upper limit for machining
MEMS Spherical film	Good repeatability	Complex process, high cost	Applicable and developable direction

frequency. In **Figure 9**, it illustrates the effectiveness of the method of preparing UHF self-focusing by sputtering ZnO film with Al as the substrate, and the process stability of this method is much better than LN spherical pressure focusing.

## MEMS Spherical Film

There is another way to realize transducer self-focus, which is a complete MEMS process. As shown in **Supplementary Figure S15**, the dome-shaped-diaphragm transducers (DSDT) (Feng et al., 2005) fabrication uses spherical balls to precisely shape wax molds, onto which parylene is deposited as a support layer for the DSDT. Piezoelectric ZnO film is sputter-deposited on the parylene dome diaphragm. E-Solder silver epoxy is placed and cured on the back surface to function both as an acoustic backing and as structural support. Quarter wavelength thick parylene is deposited on the front side of the wafer for acoustic matching. The fabrication technique for the DSDTs is meant for low-cost mass production of the devices for high-frequency biomedical imaging. This method successfully prepared a 200 MHz UHF transducer.

## Summary of This Section

Through the broader understanding of ultrasonic transducers' focusing method, we can understand the difference between UHF devices' focusing and low-frequency devices' focusing. **Table 5** presents these focusing methods' summary, which can compare the differences of these methods more intuitively.

## ACOUSTIC ENERGY TRANSMISSION MATCHING

### Description of This Section

When the ultrasonic wave is emitted from the ultrasonic transducer into the propagation medium, due to the large difference in acoustic impedance between the piezoelectric material and the propagation medium, most of the energy will be reflected, which leads to the low working efficiency of the ultrasonic device (**Figure 10**). In the low-frequency range, ceramics can be composited (Smith, 1986; Hou et al., 2018; Lin et al., 2018; Fei et al., 2019; Chen et al., 2020; Lin et al., 2020) to make the material acoustic impedance close to the propagation medium, improving energy transmission

efficiency. The metamaterials mentioned in *Material Selection of Ultrasound Generation* section also have applications in acoustic impedance matching (Li et al., 2017; Liu et al., 2018). These two methods both perform impedance matching by changing the spatial structure of the piezoelectric material. Although very effective, these operations are difficult to achieve in the UHF range. Therefore, we usually prefer to select the method by adding a matching layer to the piezoelectric material or lens surface for acoustic impedance matching in UHF. As the simplest and most effective matching method, quarter-wavelength matching (Kossoff, 1966; Desilets et al., 1978; Rhee et al., 2001) has been active from the initial Mason model (Mason, 1948; Sittig, 1972) to the improved KLM model (Krimholtz et al., 1970; Leedom et al., 1971). Although easy to use, this method requires materials with specific acoustic impedance for matching. To obtain the matching layer with specified acoustic impedance, it is a general method by dope high acoustic impedance particles into low acoustic impedance materials. However, it is difficult to get a few microns or even sub-micron size for the doped particle. For this problem, the Mass-spring model (Toda and Thompson, 2010) and the Transmission line matching network (Ma et al., 2015) are introduced for the UHF ultrasonic devices' matching layer design. Furthermore, they also provide a good solution for the precise control of the matching layer's thickness. The research situation of these two methods will show in the follow-up.

### Novel Polymer-Metal Matching Layer

In 2010, M. Toda and M. Thompson (Toda and Thompson, 2010) proposed a novel multi-layer polymer-metal structure for use in ultrasonic transducer impedance matching (Toda and Thompson, 2012; Brown et al., 2014) which is based on mass-spring model. In **Figure 11** (Fei et al., 2015) we can see, after adding a metal-polymer structure matching layer to the ultrasonic transducer, its echo amplitude and bandwidth have been improved effectively. This method does not require materials with specific acoustic impedance and only needs to design metal and polymer layers of different thicknesses in combination with material characteristics to achieve the purpose of improving acoustic energy transmission. This laminated matching layer is conducive to the batch

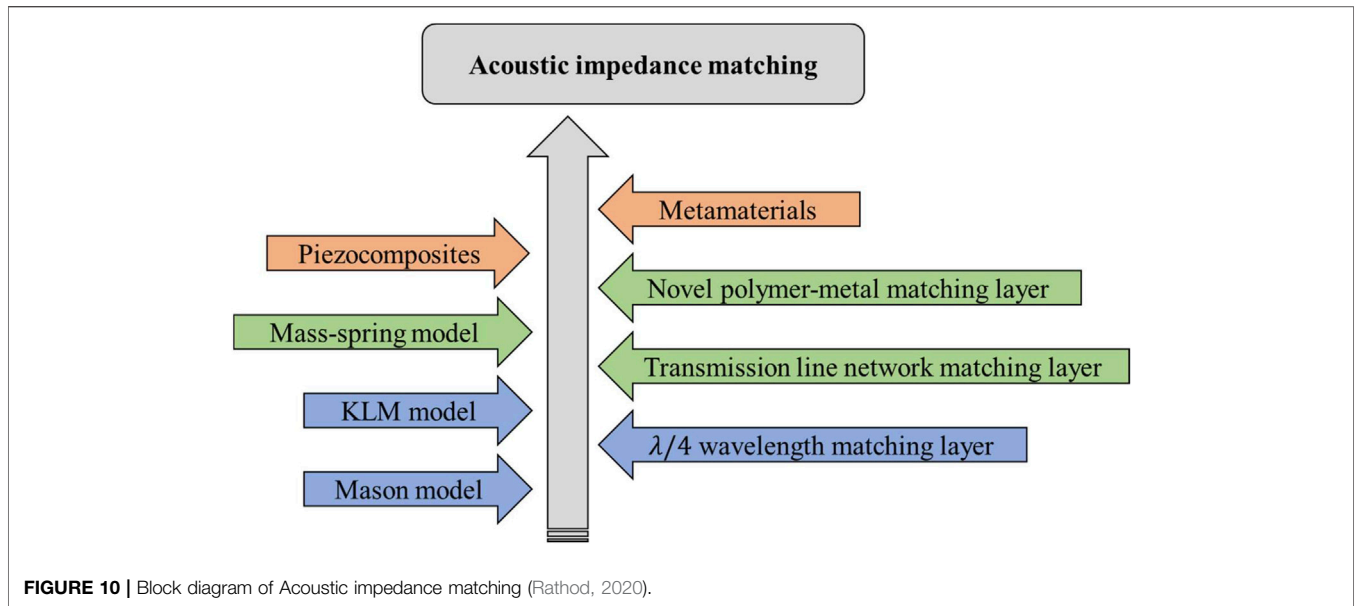


FIGURE 10 | Block diagram of Acoustic impedance matching (Rathod, 2020).

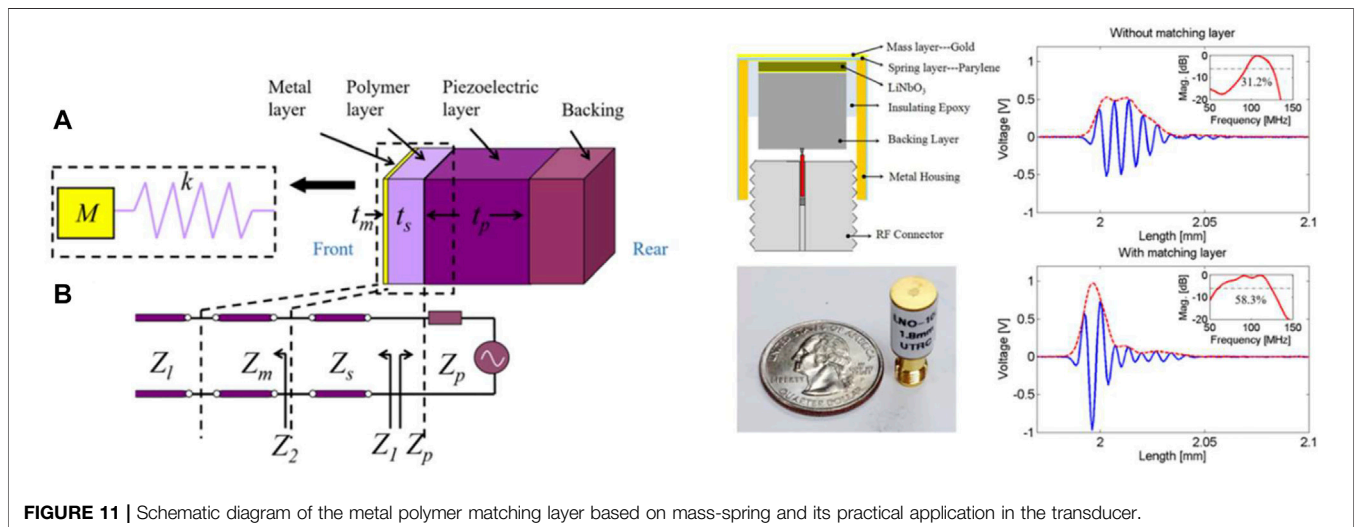


FIGURE 11 | Schematic diagram of the metal polymer matching layer based on mass-spring and its practical application in the transducer.

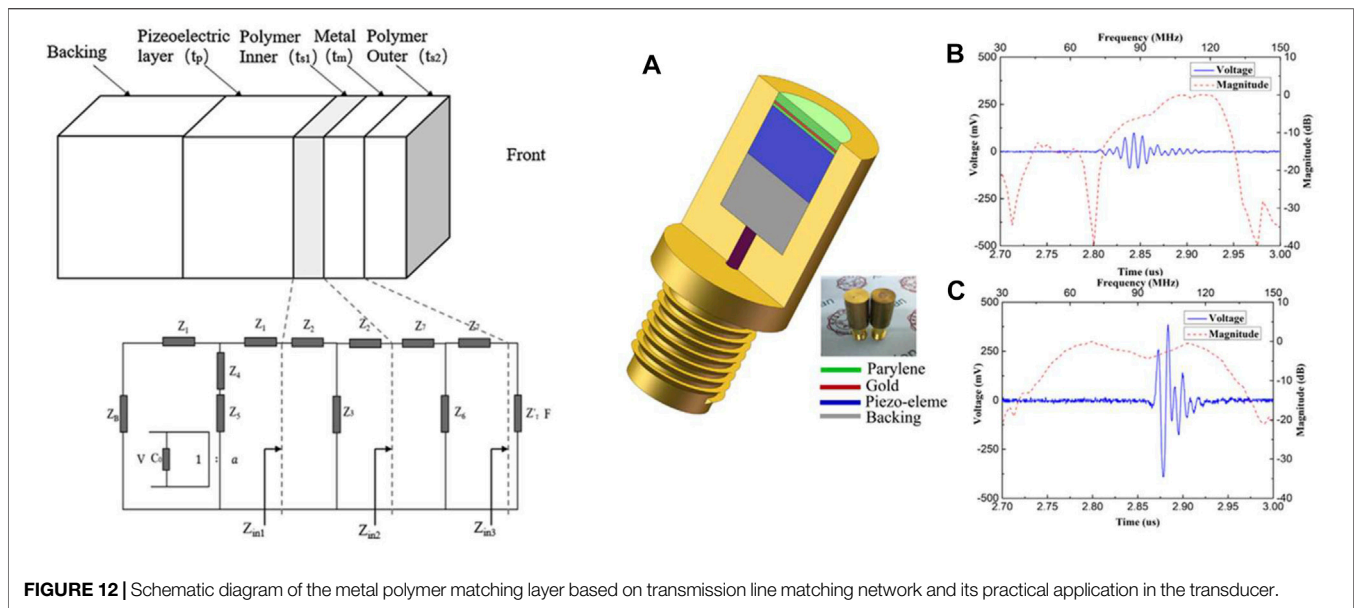
operation of the matching layer of the transducer and provides a feasible idea for the effective matching of ultra-high frequency ultrasonic devices.

### Transmission Line Network Matching Layer

The transmission line matching network is implemented based on the KLM model. The acoustic impedance matching layer is designed by equating the acoustic parameters to the transmission line parameters and connecting them with the acoustic ports of the KLM model as shown in Figure 12 (Yang et al., 2020). It can be seen from the figure that after adding the matching layer, the echo does have a significant improvement. Therefore, the transmission line matching network is also an effective way to UHF transducer’s energy transmission matching.

### Summary of This Section

Piezoelectric composites and metamaterials are not suitable for improving the acoustic energy transmission matching of ultra-high frequency ultrasonic devices due to the difficulty of actual operation in the high-frequency range. The traditional quarter matching layer is not suitable for UHF ultrasonic devices due to the specific acoustic impedance. Mass-spring and transmission line matching networks can achieve high-efficiency acoustic energy transmission by combining multi-layer materials with different acoustic impedances. Theoretically speaking, the design and implementation process of the matching layer is compatible with the MEMS processing technology, with high repeatability and good development prospects. However, we should also consider the attenuation caused by the multi-layer matching layer



itself when designing the matching layer, so the acoustic impedance matching effect and the impact of material attenuation should consider comprehensively. Artificial intelligence (Li et al., 2021a) has become popular in recent years is good at finding the optimal solution among multiple factors. In the design of multi-layer matching layers, there may be a lot of room for development.

## CONCLUSION

This article starts with the introduction of the selection of materials for UHF ultrasonic transducers. First, it explains the reasons why the most commonly used ceramic materials cannot be used in the preparation of UHF devices and then mentions the more popular relaxation-based materials, but they also have disadvantages. Therefore, it is not suitable for making UHF devices. The excellent material properties of LN single crystal make it occupy a place in UHF devices, from 100 to 500 MHz, but its difficult processing flow makes it difficult to break through the higher frequency limit. In addition, the processing flow is unstable, and the uniformity of the device caused by this makes it difficult to carry out mass production.

Things are always moving forward. The development of piezoelectric film materials has injected new impetus into the preparation of UHF transducers. Piezoelectric films prepared based on traditional ferroelectric materials solve the problem of difficult thickness control, and the piezoelectric films retain the excellent piezoelectric properties of bulk piezoelectric materials to a certain extent, and the UHF devices prepared by them have better performance. But this method can only be said to be a step to improve the thinning of piezoelectric materials in the traditional transducer manufacturing

process. Due to the high temperature of densification and annealing during the preparation of piezoelectric film materials, the preparation of piezoelectric films and the production of transducers cannot be completely compatible. This leads to secondary processing of the prepared piezoelectric film, which is also quite difficult in actual operation. How to grow the piezoelectric film and the preparation of the transducer has good process compatibility is a very critical issue, and it is hoped that this problem can be solved through continuous process improvement in the future.

The development of the semiconductor industry has made MEMS technology increasingly mature, and piezoelectric films made of ZnO and AlN, which are commonly used semiconductor materials, have also joined the family of ultra-high frequency ultrasonic transducers. The mature MEMS technology makes the piezoelectric film and the transducer preparation compatible and does not require secondary processing. The preparation of the piezoelectric film is a step included in the MEMS transducer preparation process. This gives a better guarantee for the consistency of UHF devices and provides a basis for mass production. But all things have advantages and disadvantages. The disadvantage of using semiconductor materials to replace traditional ferroelectric materials is that the piezoelectric performance is relatively poor. Piezoelectric materials determine the final performance of the device, so the problem here is how to improve the piezoelectric performance of the material. There have been a few reports on this aspect of research, such as the above-mentioned modification of Sc doping and Yb doping to improve the piezoelectricity of AlN. This is a key issue that requires more researchers to join.

In addition to material selection, the focus design of UHF ultrasound devices is another key point. At present, the most

commonly used focusing methods in UHF ultrasound devices are acoustic lens focusing and self-focusing. There are also a certain number of reports on UHF ultrasound devices in this regard. This article also mentioned more focusing methods currently used in low-frequency bands, such as spherical pressure focusing, mechanical focusing, and acoustic lens focusing. There are also some interesting focusing methods, such as ultrasonic super-surface, liquid lens focusing. By understanding these various focusing methods, we can diverge our thinking. When we encounter problems in the focus design of UHF ultrasound devices, it may provide us with clever solutions.

The last key point mentioned in this article is the problem of acoustic energy transmission. As we all know, the propagation of sound requires a medium. In the application of UHF ultrasonic transducers, the medium we mentioned is usually water, and the acoustic impedance of water is only 1.5MRlays, but piezoelectric materials are often much larger than this. If no matching layer is added, the acoustic energy is directly emitted from the piezoelectric material into the water, and most of the energy will be reflected due to the large acoustic impedance difference. This will cause the device to work very inefficiently. The traditional quarter acoustic impedance matching layer has explained why it is not suitable for UHF ultrasonic devices. A new design method of metal-polymer structure matching layer is mentioned, and its applicability in ultra-high frequency ultrasonic devices is explained.

## AUTHOR CONTRIBUTIONS

JC was responsible for collecting, sorting out relevant information and writing the paper. Other authors provided advice and help. All authors contributed to the article and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmats.2021.733358/full#supplementary-material>

**Supplementary figure S1** | Schematic diagram of acoustic tweezers (left) and ultrasound scanning microscope (right).

**Supplementary figure S2** | Ceramic grains under the microscope.

**Supplementary figure S3** | A photograph of LN transducer and cross section of piezoelectric layer (left); High resolution ultrasound image of zebrafish eye (right).

**Supplementary figure S4** | Cross section of 20  $\mu\text{m}$  PZT film.

**Supplementary figure S5** | Pulse echo and FFT of 100 MHz PZT thick film transducer (top); Experimental pulse echo and FFT of 150 MHz PZT thick film transducer (bottom left); Simulated pulse echo and FFT of 150 MHz PZT thick film transducer (bottom right).

**Supplementary figure S6** | A photograph of 300 MHz transducer (top left); Schematic diagram of 0–3 composite PZT film (top right); time-domain pulse/echo response (solid line) and frequency spectrum (dashed line) of 100–300 MHz transducer (bottom).

**Supplementary figure S7** | A photograph of 193 MHz KNN-LSO needle planar transducer (top left); schematic diagram of 225 MHz KNN/BNT piston focusing transducer (bottom left); time-domain pulse/echo response and frequency spectrum of 193 MHz KNN-LSO needle planar transducer (top right); time-domain pulse/echo response and frequency spectrum of 225 MHz KNN/BNT piston focus transducer (lower right).

**Supplementary figure S8** | Time-domain pulse/echo response (solid line) and frequency spectrum (dashed line) of 170–320 MHz KNN/BNT transducer.

**Supplementary figure S9** | Frequency curve of the dielectric coefficient of xPMN-PT-(1-x)PZT composite film under different PZT doping ratios (left); time-domain pulse/echo response (solid line) and frequency spectrum (dashed line) of 0.9PMN-PT-0.1PZT composite film transducer (right).

**Supplementary figure S10** | Ferroelectric hysteresis loops of PMN-PT-PZT composite film under different Ag doping concentration (top left); curve of influence of Ag concentration on the dielectric constant of PMN-PT-PZT composite film at 1 KHz (top right); a photograph of silver-doped PMN-PT-PZT needle transducer (bottom left); time-domain pulse/echo response (solid line) and frequency spectrum (dashed line) of silver-doped PMN-PT-PZT needle transducer (bottom right).

**Supplementary figure S11** | Preparation process of spherical pressure focusing transducer.

**Supplementary figure S12** | A photograph of needle type mechanical focused ultrasound transducer (top left); piezoelectric materials after mechanical dimpling under optical microscope (top right); IVUS mechanical focus transducer preparation process (bottom).

**Supplementary figure S13** | Two types of acoustic metasurface lenses and simulation diagram of the focusing effect of two acoustic metasurface lenses.

**Supplementary figure S14** | Schematic and physical image of liquid lens.

**Supplementary figure S15** | The flow chart of prepare Dome-Shaped-Diaphragm Transducers (left) and photographs of Dome-Shaped-Diaphragm Transducer (right).

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