A CMUT-based gas density sensor with high sensitivity

To cite this article: Libo Zhao et al 2019 J. Micromech. Microeng. 29 115012

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1. Introduction

As a fundamental physical property, density is an important thermo-physical parameter, which is closely related to the physical and chemical properties of the majority of materials, such as optical scattering, fluid phase change, thermal convection and mixing efficiency [1]. In engineering applications, the measurement of fluid density can provide basic data for scientific research of fluid mechanics, thermo-physical science, industrial control, energy, power and other engineering applications [2–4].

To ensure product quality, saving energy, reducing raw materials and strengthening economic accounting, there is a wide range of requirements for the measurement and control of various gas media in modern process automation, which makes gas density measurement with high-precision...
an urgent requirement. In addition, since the density of a gas mixture is related to composition, the composition measurement in situ applications can also be replaced by gas density measurement [5].

Resonant sensors are promising in fluid density measurement owing to their advantages of high accuracy, high sensitivity and fast response. When the resonant sensors are immersed in a fluid, the fluid will interact with the vibrating structure. It can be equivalent to an additional mass acting on the sensitive structure, causing a shift of the resonant frequency [6]. Due to the small volume, high integration and low power consumption, microelectromechanical systems (MEMS) cantilevers [7] and piezoelectric resonator-based density sensors [8, 9] are mostly used to measure fluid density. Kim analyzed the flexural wave propagations on the vibrating micro-cantilever and completed the gas density measurement [10]. The micro-cantilevers with different shapes, dimensions and operation modes demonstrated the highest sensitivity of 15.128 Hz · kg⁻¹ · m⁻³ [11]. Piezoelectric-excited millimeter-sized cantilevers have also been studied [12, 13], and can measure the change of gas density to as little as 0.088 g cm⁻³ with sensitivity equivalent to 20.408 Hz · kg⁻¹ · m⁻³. Ikehara also designed a high quality-factor silicon cantilever for a low detection-limit resonant mass sensor operated in air, and the quality-factor was high as 1550 [14]. Manzaneque designed density-viscosity sensor based on piezoelectric MEMS resonator and the sensitivity was 8.81 × 10⁻⁶ g · s ml⁻¹ [15].

A capacitive microfabricated ultrasonic transducer (CMUT) is similar to a parallel plate capacitor, which consists of the movable membrane (top electrode), cavity and fixed substrate (bottom electrode). When a DC bias voltage (V_{DC}) is applied the electrodes, the membrane will be pull down by the electrostatic force. Then, a small AC voltage (V_{ac}) with a certain frequency is also applied to them to generate an alternating electrostatic force, so the membrane will vibrate, which makes the CMUT capable of working as a resonator sensor or ultrasonic transducer.

Since capacitive microfabricated ultrasonic transducers (CMUTs) have the advantage of wide bandwidth, high resonant frequency, high electromechanical coupling coefficient, perfect integration with integrated circuits (ICs), feasible capability of array and small volume, they are generally used for imaging [16] and non-destructive testing [17]. Meanwhile, based on mass loading, the functionalized CMUTs can also be used for biochemical detection with high measuring sensitivity, for example, taking measurements of specific volatile organic compounds and sulfur dioxide [18-20]. Owing to the high resonant frequency, it was able to achieve higher measuring sensitivity, making it a potentially high-performance density sensor. Thränhardt [21] showed that CMUT-based sensors can be used for measuring fluid density, even though no final experimental verification has been found.

In this paper, a CMUT-based gas density sensor is developed. Combined with the fluid added mass model and the electromechanical coupling reduced order model of the CMUT in vacuum, the relationship between gas density and resonant frequency of CMUT is established. Using this theory, the resonant frequencies of a CMUT with different cell structural parameters under different gas densities are obtained by Matlab R2014(a), the relationship between gas density and resonant frequency of the CMUT is extracted with good linearity. Subsequently, the influences of structure parameters and bias voltage on the density measuring sensitivity (DMS) of CMUT-based density sensors are further analyzed. Then, the CMUT-based gas density sensor is fabricated using low-temperature direct wafer-bonding technique [22], and a gas density detection platform with the mass flow controller (MFC) is established. At last, the resonant frequency and phase-frequency curves of the CMUT-based density sensor under different bias voltage and different gas densities are obtained. Experimental results indicate a linear relationship between gas density and resonant frequency of the CMUT-based density sensor with the Min R Squared of 0.939, and its DMS is as high as 9760 Hz · kg⁻¹ · m⁻³.

2. Theory and simulation

2.1. Theory

In the past few decades, the theoretical analysis of CMUTs have been researched in vacuum environment. In theoretical research, some of the reduced-order models have been developed to precisely calculate the resonant frequencies of circular and square membranes. With the Galerkin-weighted residual technique, the first order resonant frequency of circular membrane under electrostatic excitation can be expressed as [23]:

\[ f_{bias} = f \cdot \frac{1 - \epsilon_0 V^2 C_V}{10.4334 DR^5} \]  

where \( \epsilon_0 \) is vacuum dielectric constant, \( V \) is the bias voltage, \( R \) is the membrane radius, \( d_0 \) is the initial height of the vacuum and \( D \) is bending rigidity as follows:

\[ D = \frac{E t^3}{12 \left(1 - \mu^2 \right)} \]  

where \( \mu \) is Poisson’s ratio, \( t \) is the membrane thickness. The coefficient \( C_V \) is:

\[ C_V = \frac{5AR^6 - 3d_0R^2}{16A^2(d_0 - AR^2)} + \frac{3}{32 \sqrt{d_0A^2}} \ln \sqrt{d_0} + \sqrt{AR^2} \]  

The coefficient \( A \) is:

\[ A = \frac{84d_0^3 - QR^4 - B}{128Dd_0R^2} \]  

The natural resonance frequency \( f_0 \) of circular membrane without any external load is:

\[ f_0 = \frac{10.21}{2\pi R^2} \sqrt{\frac{D}{\rho a t}} \]  

It is well known that the Reynolds number of the fluid is proportional to its density and inversely proportional to...
its viscosity. Therefore, in the gas sensor, due to the high Reynolds number \[24\] (\(Re \gg 1\)), the influence of viscosity can be ignored, and the resonance frequency can be regarded as independent of fluid viscosity, mainly affected by fluid density. When the fluid was loaded on the membrane, it can be calculated by adding an additional effective mass factor, and the resonant frequency \(f_f\) of CMUT in the fluid can be obtained as \[6\]:

\[ f_f = f_{bias} \frac{1}{\sqrt{1 + \beta}} \]

where the additional effective mass factor is \(\beta \approx 0.669 \cdot (\rho_f R f^2_{bias} - 1)\).

Through mathematical conversion, the density of fluid can be expressed by:

\[ \rho_f = \frac{\rho_m t}{0.669 R f^2_{bias}} \left( f^2_{bias} - 1 \right) \]

In order to get the DMS, equation (7) is differentiated on both sides; the following equation is obtained:

\[ \Delta \rho_f = -\frac{2\rho_m f^2_{bias}}{0.669 R f^2_{bias}} \Delta f_f. \]

Therefore, the DMS (S) of CMUT-based density sensor is:

\[ S = \frac{\Delta f_f}{\Delta \rho_f} = \frac{0.669 R f^2_{bias}}{-2\rho_m f^2_{bias}}. \]

When there are several structure layers between the upper and lower electrodes of CMUT, the formula should be used to calculate the equivalent relative dielectric permittivity as:

\[ d_{eff} = \frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} + \cdots + \frac{d_n}{\varepsilon_{rn}} + d_0 \]

where \(\varepsilon_{rn}\) is the relative dielectric permittivity of the \(n\)th layer and \(d_n\) is the thickness of the \(n\)th layer. Therefore, the DMS of CMUT-based density sensor is related to the density, radius, thickness of the membrane and the first order resonant frequency under electrostatic excitation, which is affected by the bias voltage.

The CMUTs array is composed of several CMUT cells in parallel, and the bias voltage and ac voltage applied on each are the same. At the same time, the mutual radiation impedance of each cell in the array is ignored in the gas density sensor, so the vibration of each cell in the array is consistent and their reaction to gas is basically the same.

However, the DMS is more complicated than theoretical analysis. Firstly, the method of analysis was based on a mass-loaded model, ignoring the effect of fluid viscosity. Secondly, the DMS is actually related to the density range of the fluid in equation (9). In future research, more complicated parameters will be taken into account to obtain the DMS with high accuracy.

Table 1. The parameters of CMUT in the simulation analysis.

<table>
<thead>
<tr>
<th>The parameters</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity modulus</td>
<td>169 Gpa</td>
</tr>
<tr>
<td>Membrane density</td>
<td>2332 kg m(^{-3})</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.29</td>
</tr>
<tr>
<td>Radius of membrane</td>
<td>70 (\mu)m</td>
</tr>
<tr>
<td>The thickness of circular membrane</td>
<td>2 (\mu)m</td>
</tr>
<tr>
<td>Cavity height</td>
<td>0.53 (\mu)m</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>10 V</td>
</tr>
</tbody>
</table>

2.2. Simulation

In order to analyze the DMS of CMUT-based density sensors with the above formulas, MATLAB (2014a) is utilized for the analysis and the simulation. Firstly, the parameters as shown in table 1 are adopted for simulation analysis, and the relationship between fluid density and CMUTs resonance frequency is obtained using equation (7).

As shown in figure 1, the squared of the fluid density (1 kg m\(^{-3}\)–1000 kg m\(^{-3}\)) is inversely proportional to the resonant frequency.
frequency of the membrane, which is also obtained in equation (7). However, the linear relationship between the fluid density and the resonant frequency can still be maintained in a small density range (0.001 kg m$^{-3}$–10 kg m$^{-3}$), as shown in figure 1(b). Therefore, this property can be used to analyze the relationship between the DMS and the parameters. In other words, the slope of this linear curve can be expressed as the DMS of CMUT-based density sensor under that certain condition. In figure 1, the DMS of 7907 Hz·kg$^{-1}$·m$^3$ is obtained between 0.001 kg m$^{-3}$ and 10 kg m$^{-3}$.

**Table 2.** The linear fitting equations under different radius of circular membrane.

<table>
<thead>
<tr>
<th>Radius ($\mu$m)</th>
<th>Linear equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>$f = -23312\rho + 13350 200$</td>
<td>0.99995</td>
</tr>
<tr>
<td>40</td>
<td>$f = -14338\rho + 5211 680$</td>
<td>0.99988</td>
</tr>
<tr>
<td>55</td>
<td>$f = -10253\rho + 2751 880$</td>
<td>0.99978</td>
</tr>
<tr>
<td>70</td>
<td>$f = -7907\rho + 1692 460$</td>
<td>0.99966</td>
</tr>
<tr>
<td>85</td>
<td>$f = -6369\rho + 1140 355$</td>
<td>0.99948</td>
</tr>
<tr>
<td>100</td>
<td>$f = -5265\rho + 813 138$</td>
<td>0.99932</td>
</tr>
</tbody>
</table>

**Figure 3.** The DMS curve along with different membrane radius.

**Figure 4.** The DMS curve along with different single-variable conditions. (a) The DMS curve along with different bias voltage; (b) the DMS curve along with different cavity height; (c) the DMS curve along with different membrane thickness.

When the parameters of membrane thickness, bias voltage and cavity height are constant in table 1, the frequency-density curves of the circular membrane with different radius were analyzed in figure 2, and the linear fitting equations were
obtained to calculate corresponding DMS, which are shown in table 2.

The DMS curves along with different membrane radius is shown in figure 3, it can be seen that the DMS decreases with the increase of membrane radius. Moreover, with the increase of membrane radius, the decline of DMS gradually slows down. This is because the basic resonant frequency of the CMUT-based density sensor is higher when the membrane radius is small, which means that the DMS of the CMUT-based density sensor is also higher. Meanwhile, as the membrane radius increases, the resonant frequency begins

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane radius of circular cell</td>
<td>70 μm</td>
</tr>
<tr>
<td>Membrane length of square cell</td>
<td>124 μm</td>
</tr>
<tr>
<td>Membrane thickness</td>
<td>2 μm</td>
</tr>
<tr>
<td>Cavity height</td>
<td>0.45 μm</td>
</tr>
<tr>
<td>Thickness of top electrode</td>
<td>0.4 μm</td>
</tr>
<tr>
<td>Thickness of SiO₂ insulation layer upon membrane</td>
<td>0.2 μm</td>
</tr>
<tr>
<td>SiO₂ pillar</td>
<td>0.55 μm</td>
</tr>
</tbody>
</table>

Figure 5. The gas density sensor based on CMUTs.

Figure 6. The main fabrication process of the gas density sensor based on CMUTs. (a) Thermal oxidation; (b) etching the cavity; (c) low temperature direct wafer-bonding; (d) removing Si substrate and buried SiO₂ layer; (e) sputtering SiO₂ layer; (f) patterning the Al electrode; (g) removing the SiO₂ layer on the back of Si substrate.

Figure 7. The CMUTs array. (a) The square structure; (b) the circular structure.
to decrease and the falling speed gradually slows down. The result shows that membrane radius should be smaller in order to obtain a higher DMS.

In order to investigate the influence of membrane thickness, cavity height and bias voltage on the DMS of CMUT-based

**Figure 8.** The impedance responses. (a) and (b) The impedance and phase responses of the CMUTs with square structure; (c) and (d) the impedance and phase responses of the CMUTs with circular structure.

**Figure 9.** Schematic of detection platform for the gas density.

**Figure 10.** Gas density detection platform.

to decrease and the falling speed gradually slows down. The result shows that membrane radius should be smaller in order to obtain a higher DMS.

In order to investigate the influence of membrane thickness, cavity height and bias voltage on the DMS of CMUT-based
density sensors, the single-variable parameter method was carried out to analyze the influence of corresponding parameters. In each analysis, in addition to the single variable parameter, the other parameters still use the same constants as shown in table 1 as a matter of course. Similar to acquisition methods for the DMS curves along with different membrane radius, the above method was applied to obtain the frequency-density curves with the different single-variable parameter using linear fitting, as shown in figure 4.

In figure 4(a), the DMS curve along with different bias voltage is obtained. As can be seen, the DMS gradually decreases with the increase of the bias voltage, and the decreasing trend gradually becomes faster. When bias voltage approaches collapse voltage (49.8 V), DMS tends to an asymptote. The DMS curve along with different cavity height is shown in figure 4(b). Different from the influence of bias voltage on the DMS, when the cavity height increases, the DMS gradually increases, and the increasing trend will gradually decrease. This is because with the cavity height increases, the electrostatic force loaded on the top electrode rapidly reduces and is close to zero. The rapid reduction of electrostatic force causes the resonant frequency change to slow down gradually and tends to the limit value, that is, the resonant frequency when the bias voltage is 0 V, which leads DMS to a certain limit value.

Similar results are obtained for analyzing the influence of membrane thickness on the DMS. With the increase of thickness, the DMS increases gradually, and its increasing trend gradually slows down, as shown in figure 4(c). As mentioned above, all these phenomena are caused by the increase or decrease of the resonant frequency of the CMUT. This is because the basic resonance frequency of the CMUT is higher when the membrane radius is smaller, then the DMS of CMUT-based density sensor will also be higher. Meanwhile, as the membrane radius increases, the resonant frequency begins to decrease and the falling speed gradually slows down. The result shows that, in order to realize a higher DMS of CMUT-based density sensor, membrane radius should be smaller. When the bias voltage decreases, or the membrane thickness increases or the cavity height increases, the resonance frequency of CMUT will increase, which also improves the DMS of CMUT-based density sensor.

3. Design and fabrication

Using the low temperature direct wafer-bonding process, the gas density sensor based on CMUTs is designed in figure 5. In order to verify that conventional CMUTs elements are sensitive to fluid density, both square and circular cells were fabricated. The whole cell is composed of the top electrode, top SiO2 insulation layer, silicon membrane, SiO2 pillar, bottom SiO2 insulation layer and substrate (also as bottom electrode).

All structural parameters of the proposed CMUT-based density sensor are shown in table 3. The top electrode completely covers above the entire cavity, which means it has a same radius as the vibrating membrane. The top SiO2 insulation layer is used to separate the top electrode from the silicon membrane, which contributes to reducing the parasitic capacitance. The existence of the lower insulation layer avoids the contact between the top and bottom electrodes for the safety protection. In addition, the low resistance silicon substrate is used as the bottom electrode.

With low temperature direct wafer-bonding process, the CMUT-based density sensor chip is fabricated. The main fabrication process of the CMUT chip is shown in figure 6.

In the first step, a low resistivity silicon substrate is chosen, and through the thermal oxidation process, thermal SiO2 layers are formed on the silicon substrate, as shown in figure 6(a). Secondly, the gap is etched to form the inside cavity as well as the bottom isolation layer by etching process. Meanwhile the pillar is also obtained in figure 6(b). Thirdly, a silicon on insulator (SOI) wafer is chosen and after the chemical mechanical
polishing and RCA cleaning process, improved surface qualities of both wafers is achieved, which can insure bonding quality. Then, the low temperature direct wafer-bonding process is carried out to connect the two wafers together (figure 6(c)). Fourthly, mechanical polishing and wet etching process are used to remove the buried layer and substrate of SOI, leaving only the Si membrane (figure 6(d)). Subsequently, the top SiO₂ isolation layer is formed by sputtering process (figure 6(e)). After that, the Al/Cu layers are sputtered on the top SiO₂ isolation layer in sequence and patterned to form the top electrode (figure 6(f)). Finally, the SiO₂ layer on the back was rinsed and removed by wet etching (figure 6(g)).

With the low temperature direct wafer-bonding process, the CMUTs-based density sensor is fabricated with the membrane possessing low deformation. As shown in figure 7, the actual CMUTs array of the square structure and the circular structure are both $28 \times 28$. The impedance response of the fabricated CMUTs is shown in figure 8.

4. Experiments of gas density sensor

In order to verify the feasibility of CMUT resonators for gas density measurement, a gas density detection platform was established. As shown in figure 9, the detection platform consists of two testing gases, two MFC and an impedance analyzer. N₂ and CO₂ were used as testing gases in the experiments, which cannot react with each other chemically. When they were mixed in different proportions, the density of the mixed gas in the pipe changed correspondingly. The density of the mixed gas is related to the mixing ratio, which can be controlled by the MFC.

When the CMUT-based density sensor was immersed in the mixed gas, the impedance analyzer can sensitively detect the corresponding phase-frequency curve, the resonant frequency was also obtained under this density.

The calculation formula for the density of mixed gases was as follows:

![Figure 12. The curves of gas density-resonant frequency with different bias voltage. (a) Square CMUTs; (b) circular CMUTs.](image-url)
mixed gas, which is the sum of gases.

At this time, 10 s was required after each adjustment, so as to exhaust all the mixed gas measured in the previous measurement from the gas testing chamber. During each measurement, the impedance analyzer was used to obtain the phase-frequency curve of the CMUTs-based density sensor, then the resonant frequency of CMUTs was extracted. Each resonant frequency of CMUTs in the different mixed gas was measured three times, and the average value was taken.

According to the above steps, the mixed gases given in table 4 were tested successfully, and the corresponding resonant frequency values of CMUTs-based density sensor were obtained at different bias voltages. When \( V_a \) is 0.5 V, the testing phase-frequency curves of CMUT-based density sensor with different gas density obtained by impedance analyzer (Agilent, E4990A, USA) were shown in figure 11. It can be seen that with the increase of gas density, the resonant frequency of CMUTs decreases gradually, and the phase change range decreases correspondingly, which was consistent with the results of theoretical analysis. Meanwhile, it was also verified that the CMUT-based density sensor was sensitive to the gas density.

Subsequently, the experiments under different bias voltage were carried out and the curves of gas density and the resonant frequency were fitted with good linearity, as shown in figure 12. After data processing, the DMS of the CMUT-based gas density sensor was also calculated under different bias voltages. For square structure, when 10 V bias voltage is applied, DMS can be up to 9760 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\). When the bias voltage increases to 15 V, 20 V, 25 V and 30 V, DMS decreases to 9086 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\), 7887 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\), 6592 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\) and 4371 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\). For circular structure, when the bias voltage is to 10 V, 20 V and 30 V, DMS are 7231 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\), 6555 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\) and 3441 Hz \( \cdot \) kg\(^{-1}\) \cdot m\(^3\), respectively. After extracted, these parameters are shown in figure 13. Compared with figure 4(a), the experimental DMS is lower than the theoretical value. This is mainly because the residual stress generated in the process of fabrication leads to an initial pull-down membrane deflection, which affects the main performance parameters such as the collapse voltage and resonant frequency. Then, the DMS is affected and becomes lower. However, their trends are consistent, that is the DMS gradually decreases with the increase of the bias voltage, and the decreasing trend gradually becomes faster. In figure 13(b), when the bias voltage increased, DMS of the circular CMUT gradually decreased, and the decreasing trend gradually became faster, which was consistent with the previous theoretical analysis. According to the experimental results in figure 13(a), DMS of the square CMUT also showed a consistent influence rule with that of circular structure. Therefore, the experiment data showed the CMUT-based density sensor has good linearity and high DMS.

\[
\rho_f = (\rho_1 \times H_1 + \rho_2 \times H_2)/H_M
\]  

where \( \rho_f \) is the density of mixed gas, \( \rho_1 \) is the density of N\(_2\), \( \rho_2 \) is the density of CO\(_2\), \( H_1 \) is the volume of N\(_2\) through the MFC, \( H_2 \) is the volume of CO\(_2\) through MFC, \( H_M \) is the volume of mixed gas, which is the sum of \( H_1 \) and \( H_2 \).

Through N\(_2\) and CO\(_2\) mixing, five mixed gases with different densities were obtained in table 4, the densities of which ranged from 1.16 kg m\(^{-3}\) to 1.83 kg m\(^{-3}\) at 0 °C.

According to the gas density detection method proposed in this paper, the experimental platform is shown in figure 10. Throughout the experiment, the pressure regulating valves for N\(_2\) and CO\(_2\) were set at 0.11 MPa to ensure a constant pressure environment. Then, the mixed gas with a certain density was obtained by adjusting the two MFCs. At this time, 10 s was required after each adjustment, so as to exhaust all the mixed gas measured in the previous measurement from the gas testing chamber. During each measurement, the impedance analyzer was used to obtain the phase-frequency curve of CMUTs-based density sensor, then the resonant frequency of CMUTs was extracted. Each resonant frequency of CMUTs in the different mixed gas was measured three times, and the average value was taken.

5. Conclusion

As a resonant sensor, the CMUTs-based gas density sensor is proposed in this paper. Combined with the fluid added mass model and the electromechanical coupling reduced order model of CMUTs in vacuum, the relationship between gas density and resonant frequency of CMUTs was established. Matlab R2014(a) is used to analyze the above theory, and the results show that the fluid density has a fine linear relationship with the resonant frequency of CMUTs within the...
gas density range (0.001 kg m$^{-3}$–10 kg m$^{-3}$). Subsequently, the influences of structural parameters and bias voltage on the DMS were further explored. It was shown that when the bias voltage decreased, or the membrane thickness increased or the cavity height increased, the resonant frequency of CMUTs would increase, which also realized a higher DMS.

At last, the density detection experiments were carried out, and the phase-frequency curves and resonant frequency of CMUTs-based density sensor in the different mixed gas under different bias voltages were obtained based on the gas density detection platform. Experimental results verified the excellent linear relationship between gas density and resonant frequency of CMUTs, as well as the influence of bias voltage on DMS. The highest DMS for square structure of cantilever sensors with asymmetric anchor exhibit picogram sensitivity in liquids Sensors Actuators B 153 64–70.

Acknowledgments

This work was supported in part by the National Key Research & Development (R&D) Program of China (Grant No. 2016YFB0501600), the National Natural Science Foundation of China (Grant Nos. 51875449, 518200, 51421004, 91748207 and 51805423), the Key Research and Development Project of Shaanxi Province (Grant Nos. 2018ZDXM-GM-103 and 2018ZDCXL-GY-02-02), the 973 Program (Grant No. 2015CB057402), the Fundamental Research Funds for the Central Universities (Grant No. xjj2017165), the 111 Program (Grant No. B12016), the Project of Key Industrial Technology Innovation of Suzhou City-Prospective Application Research (Grant No. SYG201721), and the International Postdoctoral Exchange Fellowship Program (Grant No. 20180067).

ORCID iDs

Libo Zhao https://orcid.org/0000-0001-6101-8173

References


[22] Libo Z et al 2017 Fabrication of capacitive micromachined ultrasonic transducers with low-temperature direct wafer-bonding technology Sensors Actuators B 264 63–75
