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Air-gap type film bulk acoustic resonator using flexible thin substrate

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Abstract

This paper addresses the utilization of an ultra thin silicon wafer with thickness of 50 μm to fabricate film bulk wave acoustic resonator (FBAR) generating resonant motion at 2.5 GHz which can be applied to more flexible and accumulated microsystems. As the information and communication technology starts to improve, smaller and lighter systems are needed to be flexible in a worldwide market. To accomplish this many ideas on making the heavy and rigid pieces, such as RF filter or duplexer, thin FBAR using microelectromechanical systems technology is presented in this paper. As we fabricate the FBAR using thin silicon wafer with thickness of 50 μm, it is possible to realize integrated flexible microsystems and acquire properties better than the existing devices. The resonance characteristics of thin FBAR are predicted through MATLAB simulation and then thickness of electrode and piezoelectric thin film optimized are acquired. A parallel resonance frequency is measured at 2.487 GHz. The insertion loss, *Q*-factor, and K^2_{eff} are also 1.368 dB, 996.68, and 3.91%, respectively.

Keywords: Ultra thin silicon wafer; Flexible microsystems; Thin FBAR; Resonance characteristics

1. Introduction

Recently, as the wireless telecommunication technology continues to improve rapidly, we have used electronic equipments with various functions, such as portable cellular phone, personal lap-top computer, and so on. It is continually being researched to meet the intelligent microelectromechanical systems (MEMS) technology which micromachining technology and integrated circuit technology are merged into. Especially, mobile communication devices which have a flexible substrate are needed to realize RF components which are lighter and smaller than the existing devices.

As the communication systems such as global positioning system (GPS), intelligent transport systems (ITS), and handheld mobile phones are developed, higher operating frequency of devices will be needed [1]. It is difficult to obtain the low power consumption and low insertion loss. Therefore, we select thin microwave device, thin film bulk wave acoustic resonator (FBAR), as the solution of these problems. FBARs use an acoustic resonance phenomenon of the piezoelectric materials such as ZnO or AlN. Acoustic wave propagation velocity is about 10^{-3} to 10^{-4} times lower than that of electromagnetic waves. As a result, low velocity affords sufficient miniaturization in microwave acoustic resonator. If FBAR will be used as filter, a good electrical power capability, unlimited range characteristics, and the reduced size can be obtained, compared with the ceramic filter and surface acoustic wave (SAW) filter [2–5]. General structure of FBAR is composed of top electrode, bottom electrode, and thin film piezoelectric material sandwiched between top and bottom electrodes [6]. If electric power is supplied into two electrodes, acoustic wave occurs in the piezoelectric material. It is confined between two electrodes, and thus becomes standing wave.

The structure of FBAR is largely classified into three types, such as Bragg reflector, back-etched, and air-gap [7]. The substrate must be etched completely away in the back-etched type FBAR and the thickness of multilayer must be controlled in the Bragg reflector type FBAR. On

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the other hand, the air-gap type FBAR has simple fabrication processes, compared with other types because it has the silicon substrate under membrane fabricated by anisotropic etching. In this paper, air-gap type FBAR using thin substrate is used as the solution to these problems and is more stable than other types. Also, FBAR using thin substrate has the flexibility and so the leakage current can be reduced when applied to high frequency circuit.

$$Z = \frac{1}{j\omega C_0}\left[1 - \frac{K^2}{1+K^2}\frac{\tan(kh)}{kh}\frac{(z_{top}-z_{bot})\cos^2(kh) + j\sin(2kh)}{(z_{top}-z_{bot})\cos(2kh) + j(1-z_{top}z_{bot})\sin(2kh)}\right] \quad (1)$$

2. Thin FBAR design

Fig. 1 shows the result of the MATLAB simulation and variables used in simulation are material coefficients

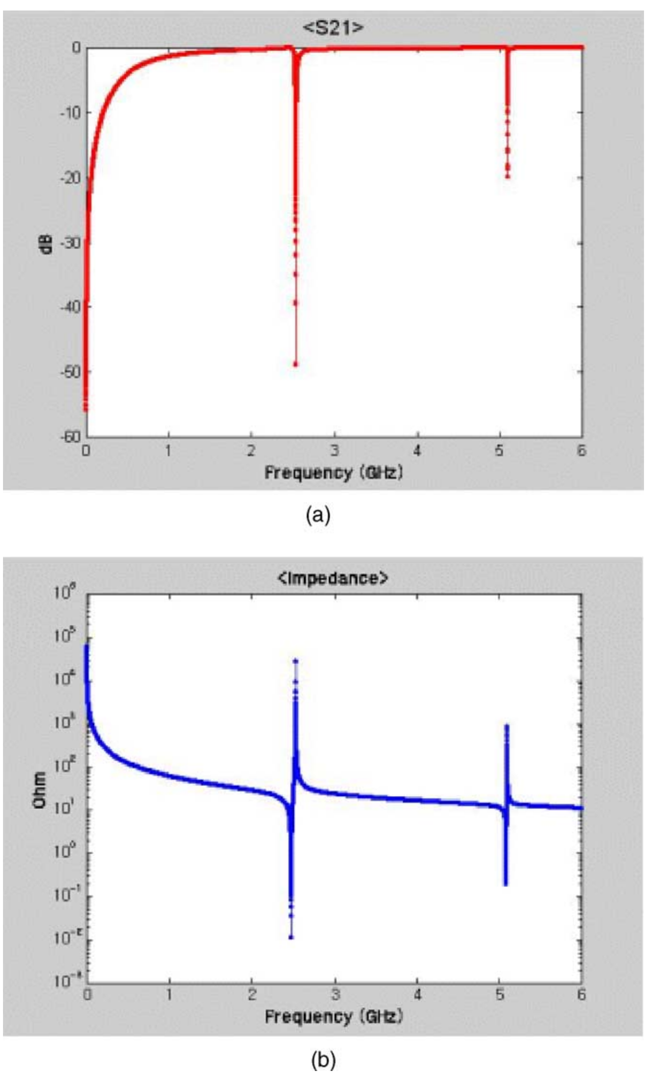

Fig. 1. MATLAB simulation of FBAR: (a) S_{21}; (b) input impedance.

(Table 1, acoustic parameters of bulk materials and thickness of each thin film for FBAR from Kino & Auld & Rosenbaum (shlee: 4/28, 2002)). The proposed thin FBAR is composed of top electrode, bottom electrode, and thin film piezoelectric material between top electrode and bottom electrode [6]. To control the resonance frequency, the impedance equation (Eq. (1)) using transmission line theory is proposed [6]

$$z_{top} = Z_{top}\left[\frac{0 + jZ_{mo}\sin(k_{mo}t_{mo})}{Z_{mo}\cos(k_{mo}t_{mo}) + 0}\right] \quad (2)$$

$$z_{bot} = Z_{mo}\left[\frac{Z_{si}\cos(k_{mo}t_{mo}) - jZ_{mo}\sin(k_{mo}t_{mo})}{Z_{mo}\cos(k_{mo}t_{mo}) - jZ_{si}\sin(k_{au}t_{au})}\right] \quad (3)$$

$$K_{eff}^2 = \frac{e^2}{c^E \varepsilon^s} \quad (4)$$

$$k = \omega\sqrt{\frac{\rho_m}{c^D}} \quad (5)$$

At this point, K_{eff}^2 is the electromechanical coupling constant of piezoelectric material (Eq. (4)) and k is the wave vector (Eq. (5)). c^E, ε^s, and e^2 are the stiffness, dielectric constant, and piezoelectric constant, respectively. c^D is the piezoelectric stiffened constant and ρ_m is the density. z_{top} and z_{bot} show the input impedance at top electrode and bottom electrode, respectively (Eqs. (2) and (3)). Besides, Z_{mo} and Z_{si} are the characteristic acoustic impedances. k_{mo}, k_{au}, t_{mo}, and t_{au} are the wave vector and thickness of the films, respectively.

Fig. 1a shows the simulated S_{21} curve of the FBAR made of $Si_3N_4/SiO_2/Si_3N_4$ film with thickness of 1 μm, and Fig. 1b shows the input impedance curve. The maximum resonance is occurred at 2.487 GHz and harmonic resonance happens at the range of 5 GHz. The resonant frequency of the thin FBAR is determined by structural and material parameters and the thickness of the piezoelectric material among them. The thickness of membrane has influence upon the quantity of harmonic resonance and insertion loss. When the thickness of AlN increases, the resonance frequency decreases. And insertion loss of the FBAR is larger and frequency shift will occur when the number of layers increases. In this paper, we are able to predict specific resonance characteristics of the FBAR, and to control the thickness of the thin films using the MATLAB simulation. Accordingly, simulation is carried out to calculate the physical dimension of each film in the FBAR as well as the resonance characteristics of the FBAR, in terms of the mass loading effect, resonance area, and microsystem reflector.

Table 1
Acoustic parameters of thin FBAR for simulation

	Stiffness (GPa)	ε^s	α (dB/cm) at 1 GHz	Z ($\times 10^6$ kg/m^{2}s)	Density (kg/m^2)
AlN	373–409	8.812	57.5	35.8828	3260
Si_3N_4	295–246	7.6	–	35.97	3440–3380
SiO_2	78.5	4	3.098	–	2250
Mo	460	–	–	63	10190

ε^s is a dielectric constant when strain is static. α and Z are the acoustic attenuation constant and characteristic impedance, respectively.

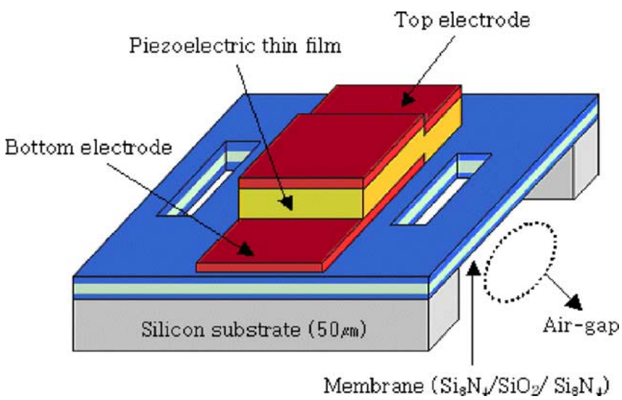

Fig. 2. Schematic view of thin FBAR.

3. Experimental

Fig. 2 shows a three-dimensional schematic of the air-gap-shaped FBAR using thin wafer. To realize the flexibility of substrate, a 4 in. p-type (1 0 0) Si wafer is etched by chemical mechanical polishing (CMP) and chemical etchant of 20 wt.% potassium hydroxide (KOH) solution. The etching temperature is 79 °C in KOH, and etching rate is 1.4 μm/min. The cross section of thin wafer is observed with the field emission scanning electron microscopy (FE-SEM). The $Si_3N_4/SiO_2/Si_3N_4$ film is formed by low pressure chemical vapor deposition (LPCVD), and etching window for membrane structure is fabricated by reactive ion etching (RIE) after Cr passivation. The RF power of RIE system is 300 W, and working pressure is 7.999 Pa. Used gases are CHF_3 (50 sccm) and O_2 (10 sccm). Surface roughness of N/O/N film is measured by atomic force microscopy (AFM) in contact mode.

Patterned Mo film is lithographically fabricated on an N/O/N wafer, which becomes a bottom electrode. The thickness of Mo film is 1000 Å. The AlN piezoelectric film with thickness of 1.2 μm is deposited on the Mo patterned wafer by RF magnetron sputter with load lock system. The base pressure of vacuum system is about 2.7×10^{-5} Pa, and RF power and working pressure are 550 W and 1.333 Pa, respectively. Used gases are N_2 (16 sccm) and Ar (20 sccm) and the deposition is performed at room temperature. The X-ray diffractometer (XRD) scanning is performed to find proper-

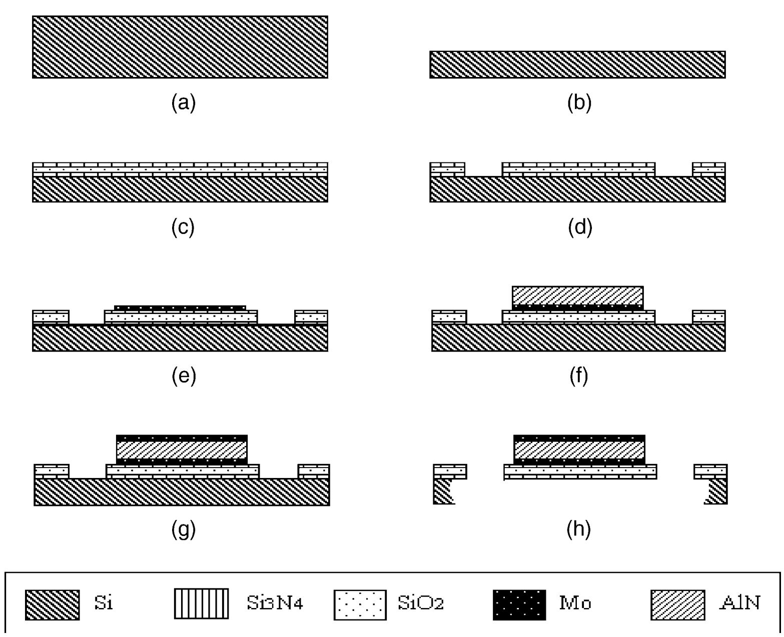

Fig. 3. Fabrication sequence of the FBAR using thin silicon wafer: (a) general silicon wafer; (b) fabrication of thin wafer with thickness of 50 μm; (c) multilayer ($Si_3N_4/SiO_2/Si_3N_4$) deposition for membrane; (d) window formation for silicon deep etching; (e) bottom electrode deposition; (f) piezoelectric material deposition; (g) top electrode deposition; (h) air-gap formation using XeF_2 etcher.

ties of deposited AlN film. Then, top electrode is also deposited on the AlN film with Mo electrode in the same way. Finally, membrane is formed by removal of silicon through etching window. Silicon is etched by a XeF_2 gas for 25 min in 1 Torr and the formed depth of air-gap is approximately 50 μm. The structure of thin FBAR is also observed with the FE-SEM, and its wafer level is shown in Fig. 8. Resonance characteristics are measured from 2.2 to 2.8 GHz using HP8753ES vector network analyzer. An illustration of a typical fabrication process is shown in Fig. 3.

4. Results and discussion

4.1. Properties of ultra thin silicon substrate

To give more flexibility to an electronic communication system, it requires a thinner fluid and atypical substrate. Especially, the FBAR applied to the RF filter is needed to have low insertion loss, high quality factor, and high electromechanical coupling coefficient (K^2_{eff}) [7]. Fig. 4a shows the flexibility of fabricated thin wafer and Fig. 4b shows cross-sectional SEM image of Fig. 4a. At this point, CMP and wet etching are essential to obtain a thin wafer with smooth surface, in the case of regular silicon wafer. Until the thickness of wafer becomes 100 μm and below, wafer is etched by CMP, and then etched in KOH solution until its thickness becomes about 50 μm. Because thin wafer has difficulty of handling and weakening of durability, it is destroyed if CMP (wet etching) only is used. To prevent against mechanical destruction, the thin wafer is glued on ordinary PR (AZ1512)-coated silicon wafer as interface layer during experiment [8,11]. Total thickness variable (TTV) of thin Si substrate is ±5 μm and surface roughness is 92.6 Å. It has the above 30° of flexibility. The fabrication flow of thin substrate has reproducibility, because it is secured by passivation layer during the thinning process in KOH solution and handling wafer used for experiment. Thin wafer of Fig. 4 affords more flexibility in components and size (weight) reduction of devices, such as bandpass filter or du-

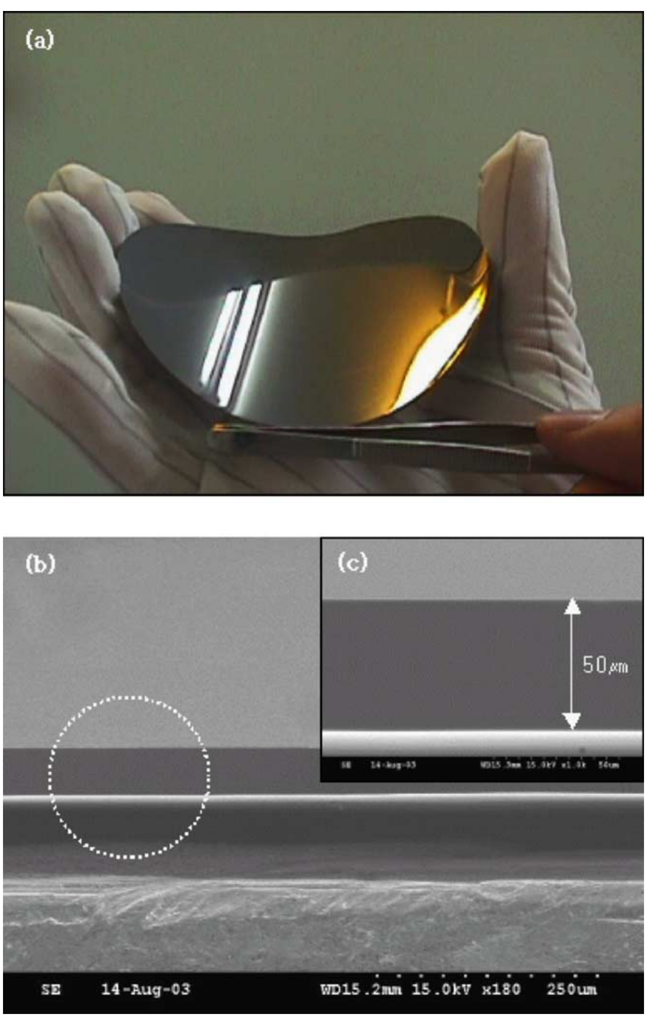

Fig. 4. Fabricated thin wafer: (a) thin silicon wafer with thickness of 50 μm; (b) cross section of thin wafer.

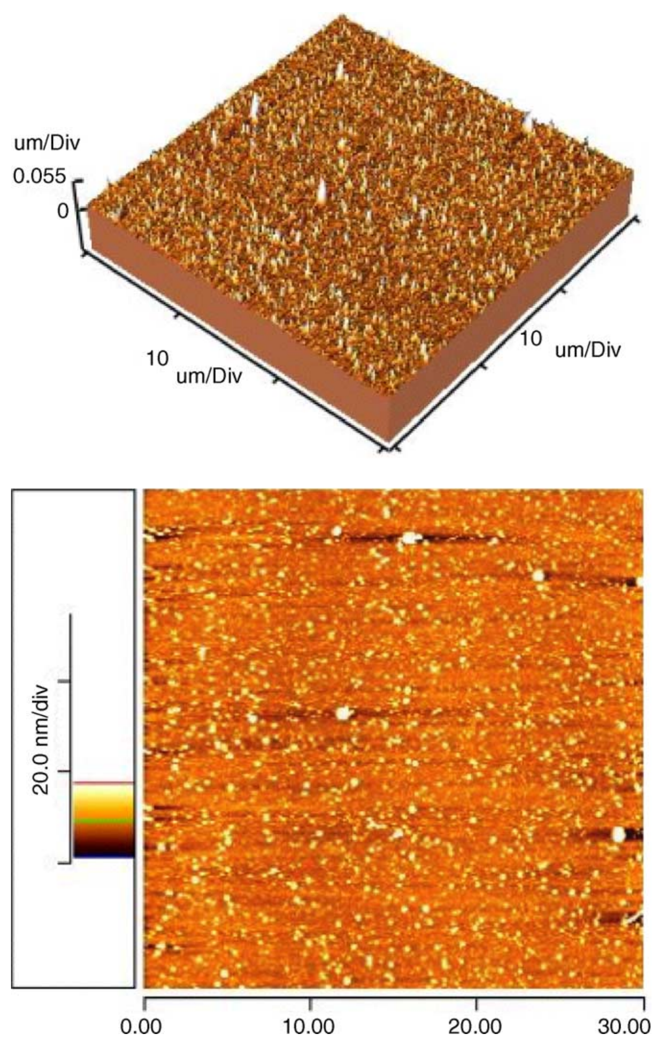

Fig. 5. AFM images of $Si_3N_4/SiO_2/Si_3N_4$ film used as membrane layer.

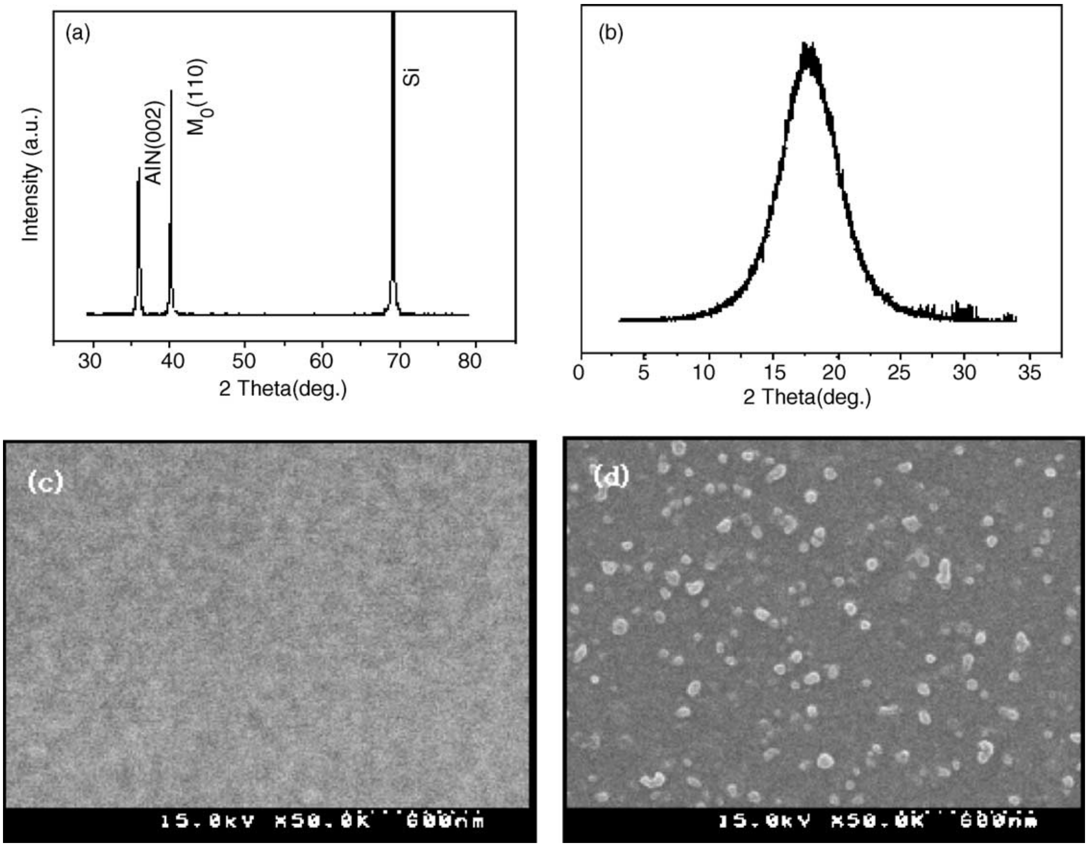

Fig. 6. Properties of thin films: (a) XRD of AlN/Mo/Si; (b) rocking curve of AlN/Mo; (c) morphology of piezoelectric layer; (d) the surface microstructure of AlN film on electrode.

plexer. Moreover, the leakage current of active device can be reduced by short electric path of thin wafer when applied to high frequency circuit.

Fig. 5 shows AFM image of 1 μm $Si_3N_4/SiO_2/Si_3N_4$ film which becomes the membrane. It shows a good surface roughness of 16.94 Å. The ideal FBAR requires that both surfaces of resonator are free surfaces such as air or vacuum. Acoustic energy is no loss, because total reflection is generated by the difference of characteristic impedance at the boundary surface. However, the thin FBAR in this paper involves membrane composed of three layers ($Si_3N_4/SiO_2/Si_3N_4$) as the supporting layer. Consequently,

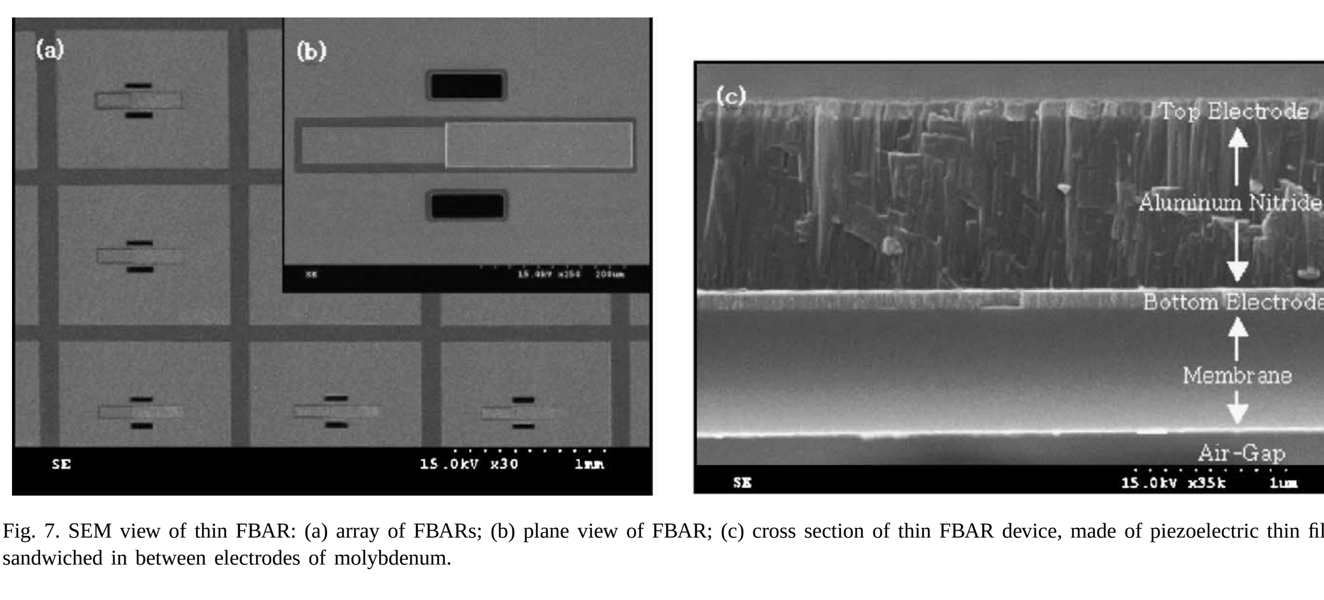

Fig. 7. SEM view of thin FBAR: (a) array of FBARs; (b) plane view of FBAR; (c) cross section of thin FBAR device, made of piezoelectric thin film sandwiched in between electrodes of molybdenum.

N/O/N film must have good properties, such as low residual stress and high density, to reduce a partial loss by membrane and an effect on harmonic resonance. Moreover, we use the membrane with several layers to reduce acoustic loss between thin films. N/O/N multilayer is used as membrane because stress generated very much when only single layer such as Si_3N_4 or SiO_2 is used.

4.2. Characteristics of air-gap type FBAR using flexible thin substrate

Generally, electrodes in FBAR play a role in the path of acoustic wave propagation. Accordingly, it is important to choose the electrode material. The face-centered-cubic (f.c.c.) metals such as Au(1 1 1), Pt(1 1 1), and Al(1 1 1) help perpendicular growth of AlN film. However, Pt and Au films need a seed layer to deposit on substrate and are difficult to be etched out. Al film is easy to be oxidized and bring about the problem of etching selectivity with an AlN [8]. In this paper, we use Mo as electrode because it is easily etched and has good acoustic wave propagation property. Fig. 6 shows XRD θ–2θ scan result and rocking curve of AlN film deposited on Mo electrode. The XRD indicates that the (0 0 2) diffraction peak of AlN/Mo film has high intensity at 36° and its full width half maximum (FWHM) value is 4.6° in rocking curve. When AlN film is oriented towards the *c*-axis perpendicular to the substrate, it has better piezoelectric properties. Accordingly, the analysis, as shown in Fig. 6, confirms what piezoelectric film has the preferred *c*-axis orientation growth, high density, and an even plane.

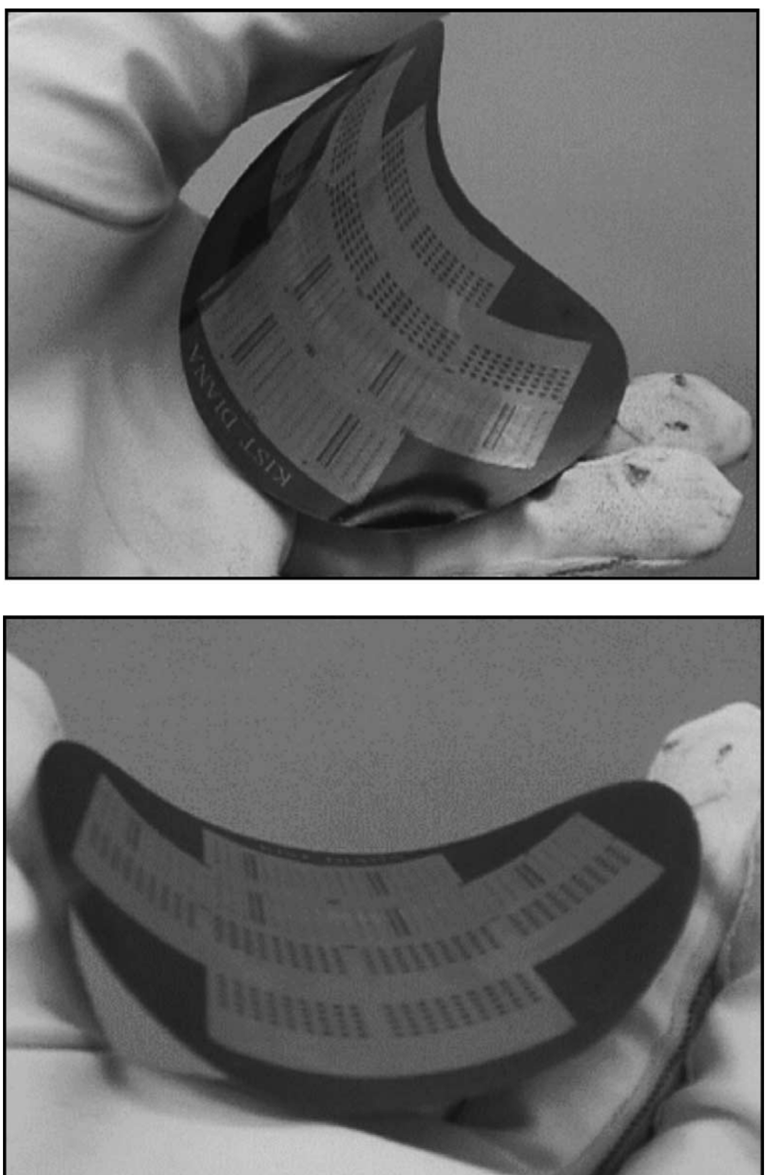

Fig. 8. Fabricated thin FBAR of wafer level with the flexibility.

The good morphology of AlN and Mo electrode are shown in Fig. 6c and d, respectively. As the surface roughness of underlying Mo film is dense and smooth, *c*-axis-oriented AlN film with better properties is grown [9].

Membrane is fabricated by silicon deep etching using XeF_2 etcher. As silicon etching by XeF_2 gas is performed, simple process and high yield can be acquired. Especially, capillary force by liquid does not generate in the air-gap because the substrate is etched more than 50 μm using an ultra thin wafer. Air-gap entirely opened under the membrane avoids the over-mode phenomenon due to the substrate loading effect. Also, XeF_2 gas has significant etching selectivity when a mixture of silicon and nitride with a ratio of 40:1 is obtained and then device can be fabricated without change of surface roughness [10].

Fig. 7a shows the SEM image of the fabricated thin FBAR device and Fig. 7b shows its cross-sectional view. The device is patterned into a 450 μm × 80 μm square at the air-gap center and active area of AlN is 50 μm × 50 μm. The air-gap shaped FBAR generates bulk acoustic standing wave at a piezoelectric thin film without little loss when RF signals are applied, as shown in Fig. 7. Consequently, the FBAR maintains piezoelectric phenomenon by most trapping of the energy in the structure. Fig. 8 shows thin FBAR of wafer level with the flexibility. It means that RF components such as duplexer or antenna can be applied to the flexible microsystems.

The resonance characteristics of thin FBAR are measured using HP8753ES vector network analyzer and microwave probe station. Fig. 9 shows the typical plot of the transmission coefficient (S_{21}) and the input impedance versus frequency for thin FBAR on ultra thin wafer. In Fig. 9a, the f_s and f_p are 2.447 and 2.487 GHz, respectively. At this point, insertion loss (IL) is 1.368 dB at f_s and 26.123 dB at f_p. Compared with the values previously reported for the air-gap shaped FBAR [10], value of IL is relatively low. IL means attenuation of acoustic energy while RF signal is applied vertically to the piezoelectric aluminum nitride. The estimated and experimental resonance frequencies are well-matched but IL is not satisfactory owing to a conductor loss of Mo electrodes. Accordingly, FBAR fabricated on the thin wafer acquires better performances than FBAR on general wafer because it has short electric path that makes less noise and uses less energy. Especially, we form air interface by making a membrane in the resonator, adopting silicon deep etching to trap the supplied acoustic energy

$$K^2_{\mathrm{eff}} = \frac{(\pi/2)(f_s/f_p)}{\tan((\pi/2)(f_s/f_p))} \tag{6}$$

$$Q = \frac{f}{2}\frac{\partial \angle Z}{\partial f} \tag{7}$$

To accomplish thin, light, and mechanical flexible device, the *Q*-factor and electromechanical coupling coefficient (K^2_{eff})

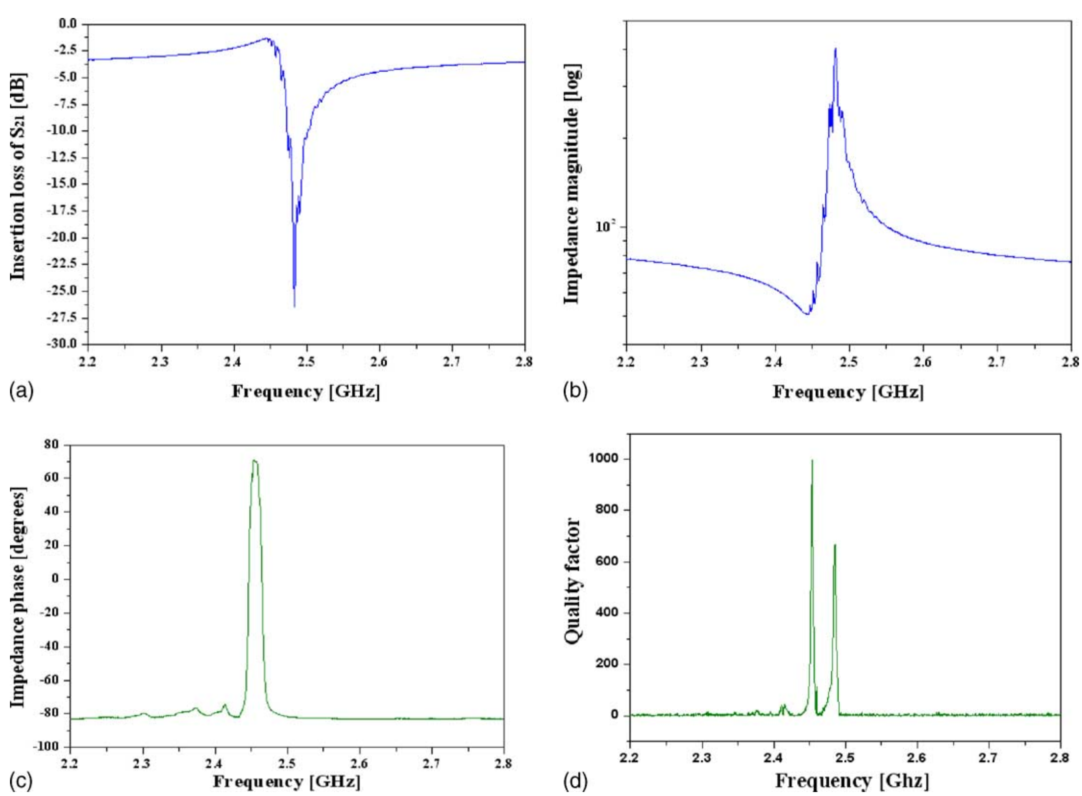

Fig. 9. Measured results of the resonance frequency: (a) transmission coefficient (S_{21}); (b) input impedance vs. frequency on thin FBAR; (c) impedance phase about the resonance frequency; (d) quality factor.

of resonator must be maximized. K^2_{eff} is the relative frequency spacing between series resonance frequency and parallel resonance frequency and also a dimensionless measure of electromechanical energy conversion efficiency. Quality factor is a measure of the resonator loss of a device. The measured Q-factors at series and parallel resonance frequencies are about 996.68 and 667.06, respectively. Fig. 9c shows the impedance phase about resonance frequency and Fig. 9d shows extracted Q-factor. Also, K^2_{eff} is approximately 3.91%. The used formulae are Eqs. (6) and (7) [1]. The used tool is advanced design system (ADS) program.

In our experiment, use of thin wafer enables to increase the Q-factor and to stabilize response of frequency on resonance characteristics. Consequently, we expect that the flexible microsystems can be realized by applying thin wafer with the flexibility.

5. Conclusion

In this paper, we fabricates the thin FBAR generating resonant motion at 2.5 GHz on the thin wafer, which has high flexibility for flexible microsystems and the ability to minimize the element. The thin FBAR is made of silicon wafer with thickness of 50 μm and membrane with multilayers ($Si_3N_4/SiO_2/Si_3N_4$). To control the resonance properties, we perform the MATLAB simulation by putting material coefficients. The series resonance frequency and parallel resonance frequency of the thin FBAR fabricated are 2.447 and 2.487 GHz, respectively. Q-factor and K^2_{eff} are measured to be 996.68 and 3.91%, respectively. We can confirm that the thin FBAR applying ultra thin wafer uses less power consumption and makes less noise because thin wafer has short electric path. Also, this technique enables to acquire low temperature process and to have potentiality of monolithic microwave integrated circuits (MMIC) using MEMS technology. Consequently, our approach will be able to give a clue to actualize the flexible microsystem and it can be applied to the micro-telecommunication wireless transmitter front-end module in the flexible skin electronics system.

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Byeong-Kwon Ju received the M.S. degree in Electronic Engineering from University of Seoul in 1988 and Ph.D. degree in semiconductor engineering from Korea University in 1995. In 1988, he joined the Korea Institute of Science and Technology (KIST), Seoul, where he was engaged in development of mainly silicon micromachining and microsensors as a Research Scientist. In 1996, he spent six months as a Visiting Research Fellow at Microelectronics Center, University of South Australia, Australia. Since 1995, he has been a Senior Research Scientist of KIST with his main interest in flexible display and silicon micromachining (MEMS). Dr. Ju is a Member of the Society for Information Display (SID), Korea Institute of Electrical Engineering (KIEE), and Korean Sensors Society.