Ultrathin single-crystalline $LiNbO_3$ film bulk acoustic resonator for 5G communication

Zijing Fang, Hao Jin✉, Shurong Dong, Leihe Lu, Weipeng Xuan and Jikui Luo

This Letter reports a high-performance film bulk acoustic resonator (FBAR) that can be applied in 5G wireless communication. The FBAR has a back-etched free-standing structure using an ultra-thin single-crystalline lithium niobate ($LiNbO_3$) as the piezoelectric film. The thin $LiNbO_3$ was obtained by the smart cut method and FBARs were fabricated by a standard MEMS process. Owing to the superior bulk-like properties of the single-crystal thin film, the fabricated FBARs have a resonant frequency of 5.0 GHz, a quality factor above 1800 and an electromechanical coupling coefficient of 2.66%, demonstrating a promising potential of FBAR filters in 5G and future 6G applications.

Introduction: The film bulk acoustic resonator (FBAR) is one of the key components of radio-frequency (RF) front-end modules for 5G wireless communication. With the rapid development of 5G technology, mobile communication systems require higher transmission rates, higher spectrum utilisation, more equipment access, and lower latency raise high demands on the performance of the relevant electronic components. Although surface acoustic wave (SAW) filters are used for current communication systems that operate at around 2 GHz, they are unable to meet the high requirements of 5G. FBAR becomes the most promising technology for high-frequency applications owing to its excellent performance [1] and potential for higher frequency. FBAR is a resonator with bulk acoustic waves and its resonance frequency is determined by the thickness of piezoelectric films, makes it possible to fabricate FBARs with frequencies up to 20 GHz for applications in future wireless communications. FBARs have been intensively researched by both industry and academia, but with frequencies mostly limited to round 2 GHz [2, 3] so far. The main limitation of high-frequency FBARs is the lack of high-quality piezoelectric film materials. The most used piezoelectric materials in FBARs are polycrystalline films, such as AlN and ZnO, prepared by magnetron sputtering technology. To obtain FBARs with 5 GHz resonant frequency or higher, thin piezoelectric layers of several hundred nanometers are required, and it is extremely challenging to obtain such thickness AlN or ZnO films with good crystal quality by conventional sputtering methods. Compared with polycrystalline films, the piezoelectric properties of single crystals such as lithium niobite ($LiNbO_3$) are much better as single-crystal materials have a very limited scattering and loss of grain boundaries and defects. Single crystal $LiNbO_3$ has achieved proper application in the field of SAW devices [4], and recently, a bulk acoustic resonator based on zy-cut $LiNbO_3$ has proposed, but the Q factor is ∼300 [5]. It is yet to be explored for $LiNbO_3$ FBARs.

In this Letter, a high-performance FBAR based on ultrathin single crystalline $LiNbO_3$ film with a back-etched cavity is proposed and fabricated. The measured resonant frequencies are about 5.0 GHz, Q factor around 1800, and k^2_{eff} 2.66%, showing superior properties as compared to those reported so far.

Modelling and device fabrication: The $LiNbO_3$ FBAR was designed and numerically analysed by the finite-element method using COMSOL Multiphysics software before fabrication. Fig. 1*a* shows the 3D structure of the FBAR device used in modelling. The FBAR has a back-etched structure, consisting of an Al/$LiNbO_3$/Au/Si free-standing device structure. It has a 50 nm thickness top Al electrode, a 530 nm z-cut single-crystalline $LiNbO_3$ piezoelectric layer, a 50 nm thickness bottom Au electrode, and a 2 μm SiO_2 supporting layer, with the remaining Si being etched from the backside. The active area of the device, which is the shared area between the top and bottom electrodes, is a pentagon shape with side lengths of 200 μm. For simple modelling, the SiO_2 supporting layer beneath the bottom electrode is not shown in the figure. With RF signal applied between two electrodes, longitudinal acoustic standing waves are generated in the thin $LiNbO_3$ film, and can be numerically modelled. The particle displacement at the resonant frequency is shown in Fig. 1*b* by using the eigenanalysis method. The maximal displacements of particles in the device occur at the bottom and top surfaces of the $LiNbO_3$ thin film, confirming that the $LiNbO_3$ film resonates in thickness longitudinal mode. Fig. 1*c* shows the simulated electrical impedance characteristic by using the frequency sweep analysis method. There are two well-defined resonance peaks at 4.820 and 4.880 GHz, corresponding to the series resonant frequency (f_s) and parallel resonant frequency (f_p), respectively. Based on the modelling results, the FBAR resonator was designed and fabricated.

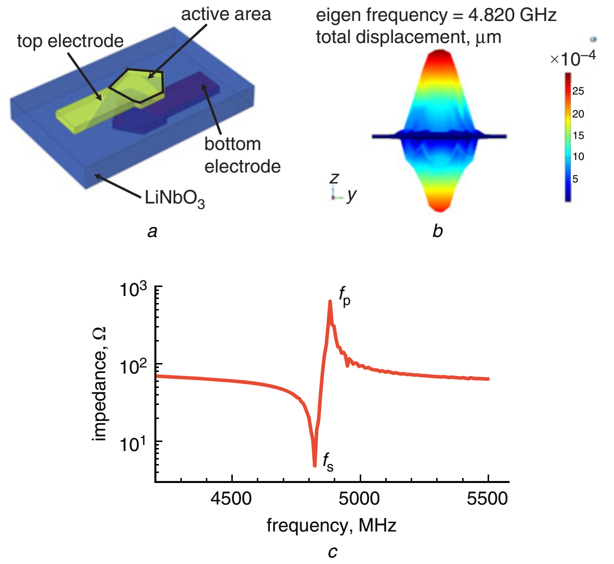

Fig. 1 *3D simulation of $LiNbO_3$ FBAR using Comsol Multiphysics*

a Illustration of 3D schematic of FBAR for simulation
b Simulated displacement at resonant frequency (cross-section view)
c Simulated electrical impedance characteristics

The fabrication process is shown in Fig. 2. First, a single-side polished $LiNbO_3$ wafer with a thickness of 400 μm (Fig. 2*a*) was cleaned, and helium ion (He^+) was implanted with energy at 115 keV, the dose is 3×10^{16} ions/cm^2 from the polished side of the $LiNbO_3$ wafer. The implantation depth of ∼550 nm was controlled by the implantation parameters to meet the thickness requirement for the 5G FBAR (Fig. 2*b*). Then, the Au electrode of 50 nm thickness was formed on the $LiNbO_3$ surface using the lift-off process and e-beam evaporation, followed by depositing a SiO_2 supporting layer of 2 μm by a plasma-enhanced chemical vapor deposition (PECVD) (Fig. 2*c*). The SiO_2 surface of the wafer was bonded to a 400 μm thickness silicon wafer by direct bonding technologies (Fig. 2*d*). Next, the $LiNbO_3$ wafer was annealed at 300 °C for 200 min so that He^+ can converge into bubbles at the interface to facilitate the following peel-off process. After peeling off (Fig. 2*e*), an ultrathin single-crystal $LiNbO_3$ piezoelectric layer bonded to a silicon wafer was obtained. The surface of the thin $LiNbO_3$ layer was then polished by chemical-mechanical polishing (CMP) to obtain a thickness around 530 nm with a roughness <10 nm (Fig. 2*f*). Then, a via through the $LiNbO_3$ for electrical contact with the bottom electrode was formed by deep reactive ion etching (DRIE) (Fig. 2*g*). The top Al electrode with a thickness of 50 nm was formed by a lift-off and magnetron sputtering process, and the bottom Au electrode was formed to the top surface as well through the via by a lift-off and e-beam evaporation. Finally, the backside Si substrate was etched by DRIE to form a back-etched FBAR structure, as shown in Fig. 2*h*.

Results and discussions: The top and bottom optical images of the fabricated FBAR resonator are shown in Figs. 3*a* and *b*, respectively. The etched circular shape cavity at the centre of the device can be clearly seen from the figures. The cavity is slightly larger than the FBAR active area to ensure the FBAR membrane is fully free-standing. A vector network analyser (Keysight E5071C) was used to characterise the electrical characteristics of the FBAR resonator with the impedance spectrum shown in Fig. 3*c*. The measured f_s and f_p of the FBAR resonator are 5.009 and 5.062 GHz, respectively, slightly larger than the designed ones. The deviations of the measured frequencies from the simulated frequencies are mainly due to the difference between the fabricated film thickness and that used in the simulation, which can be improved by precision control of CMP process and in-situ thickness monitoring in the future.

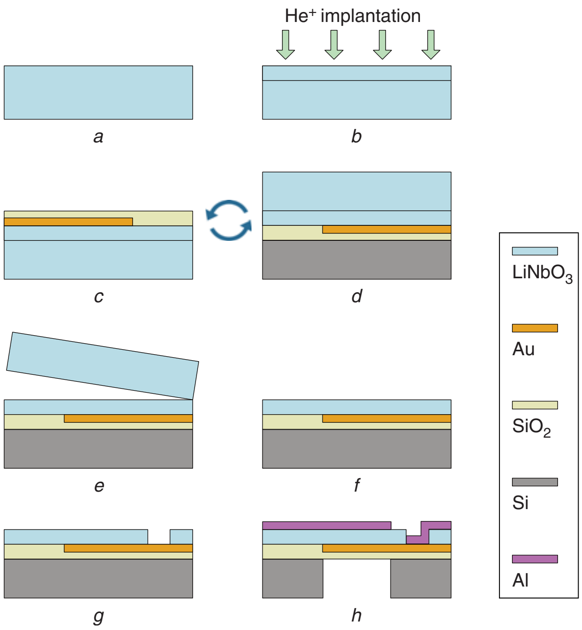

Fig. 2 *Illustration of the fabrication process for the ultra-thin single crystal $LiNbO_3$ FBAR resonator (not-to-scale drawing for clarity)*

a Prepare a polished $LiNbO_3$ wafer
b Implant He^+ ion
c Deposit Au electrode and SiO_2 supporting layers
d Turn around and bond SiO_2 surface to a Si wafer
e Peel off to obtain an ultrathin single-crystal $LiNbO_3$ layer
f Polish the $LiNbO_3$ surface by a CMP
g Form a via by DRIE
h Deposit Al electrode and etch Si substrate from backside

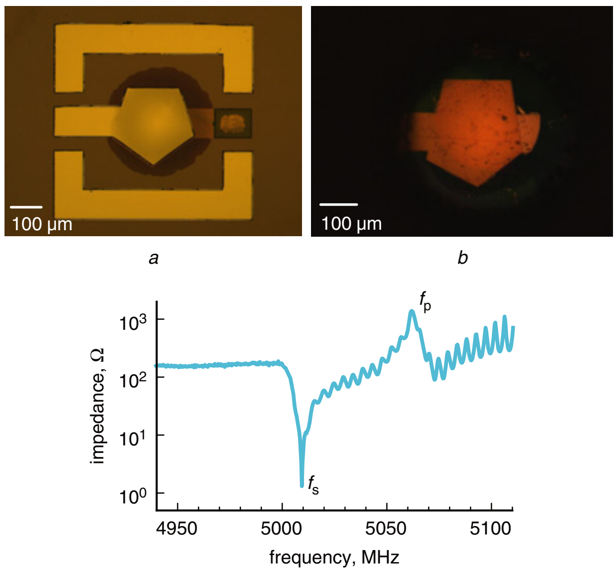

Fig. 3 *Fabricated FBAR resonator and measured electrical impedance*

a Top view image from an optical microscope
b Bottom view image from an optical microscope
c Measured electrical impedance of $LiNbO_3$ FBAR

k^2_{eff} and Q factor are the two important parameters of FBAR resonators. The k^2_{eff} was evaluated by (1), while the Q factor was calculated using the widely-used 3-dB method

$$k^2_{eff} = \frac{(\pi/2)\cdot(f_s/f_p)}{\tan\big((\pi/2)\cdot(f_s/f_p)\big)} \quad (1)$$

The calculated k^2_{eff} is 2.66%, which is consistent with the theoretical value [6]. The Q factor is up to 1800, which is much better than those of current developed 5G FBARs [5]. From the measured results, it can be seen that there are some parasitic resonance peaks that are believed to be due to the defects in the $LiNbO_3$ thin film induced by the ion implantation process. It is also possible that the backside of the FBAR substrate has not been fully etched out and the residual Si in the back cavity influences the resonance characteristics. It should be emphasised that a z-cut $LiNbO_3$ crystal wafer was used in this work only because it supports the pure thickness of longitudinal wave mode for demonstration, and other orientations of $LiNbO_3$ wafers can also be used to fabricate high-performance FBARs in a similar method.

Conclusion: In summary, we have designed and fabricated a single crystal $LiNbO_3$ thin-film based FBARs that can be applied in 5G communication. The resonant frequencies are around 5 GHz, the electromechanical coupling coefficient is 2.66%, and the Q factor is 1800. This demonstrates the possibility of high-frequency FBAR while high quality is kept owing to the excellent properties of single-crystal materials. $LiNbO_3$ FBAR shows promising applications in 5G and future 6G wireless communications.

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One or more of the Figures in this Letter are available in colour online.

Zijing Fang, Hao Jin, Shurong Dong, Leihe Lu and Jikui Luo (*Key Laboratory of Advanced Micro/Nano Electronic Devices & Smart Systems of Zhejiang, College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, People's Republic of China*)

✉ E-mail: hjin@zju.edu.cn

Weipeng Xuan (*Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University, Hangzhou 310018, People's Republic of China*)

Zijing Fang, Hao Jin, Shurong Dong, Leihe Lu and Jikui Luo: Also with Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University, Hangzhou 310018, People's Republic of China

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