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# Fatigue Characteristics of Magnetostrictive Thin-Film Coated Surface Acoustic Wave Devices for Sensing Magnetic Field

YANA JIA<sup>1</sup>, WEN WANG<sup>1</sup> , (Senior Member, IEEE), YUAN SUN<sup>1,2</sup>, MENGWEI LIU<sup>1</sup>, XUFENG XUE<sup>1</sup>, YONG LIANG<sup>1</sup>, ZHAOFU DU<sup>3</sup>, AND JINGTING LUO<sup>4</sup>

<sup>1</sup>Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China

<sup>2</sup>University of Chinese Academy of Sciences, Beijing 100190, China

<sup>3</sup>Beijing Institute of Radio Measurement, Beijing 100854, China

<sup>4</sup>College of Physics and Energy, Shenzhen University, Shenzhen 518060, China

Corresponding author: Wen Wang (wangwenwq@mail.ioa.ac.cn)

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**ABSTRACT** Magnetostrictive thin-film coated Surface Acoustic Wave (SAW) devices were promising for sensing magnetic field owing to their superior features as micro-size, fast response, and high sensitivity originated from the magnetostrictive effect. However, the magnetostriction nature in magnetostrictive thin-film causes significantly mechanical fatigue in service, deteriorating the sensor performances. In this work, the fatigue phenomenon in magnetostrictive coating was underlined by characterizing the prepared FeCo thin-film coated magnetic device cyclically. Obvious shedding was observed in FeCo coating after cyclic testing and the magnetic-sensitivity decreases significantly. One of the reasons is the weak adhesion of FeCo thin-film towards the substrate. As an available way allowing enhancement of adhesion, a Cr thin-film was employed as the transition-layer to weaken the mechanical fatigue. However, it accompanied by the issue of the reduced magnetostrictive coefficient and the obstruction in magnetostrain-transfer to piezoelectric substrate. As a result, the slump in sensitivity was observed. To address such issues, a design of dotted-pattern with Cr transition layer was employed to build the SAW based magnetic-device. High magnetic-sensitivity and excellent long-term stability were achieved because of the release of coercive force in FeCo dots and enhancement of the FeCo adhesion to the substrate.

**INDEX TERMS** Dotted-pattern, mechanical fatigue, magnetostrictive effect, SAW magnetic sensor, Cr transition layer.

## I. INTRODUCTION

The magnetostrictive materials attracted much attention for sensing magnetic field owing to their high magnetic sensitivity, fast response, high preparation efficiency, and low cost [1]–[5]. Excellent sensor performances were achieved from the sensor prototypes employing some magnetostrictive materials as FeGa, Ni, FeCo [6]–[9]. Interestingly, a new configuration of magnetic sensor was built by depositing a magnetostrictive thin-film on top of surface acoustic wave (SAW) device [10], [11]. The magnetostrain behavior originated from the magnetostrictive effect modulates

the SAW propagation velocity, and corresponding frequency shift was collected to evaluate the magnetic field to be detected. Some interesting results were constantly emerging. A magnetic-sensitivity of 31.5 ppm/mT was achieved from the sensing device with layered structure of Ni/Al<sub>2</sub>O<sub>3</sub>/IDT/LN-Y128° when device operating at 815 MHz [12]. Larger shift of 0.64% in SAW velocity was predicted from a 500 nm Galfenol thin-film coated SAW device operating at 158 MHz [13]. Analogously, a maximum SAW velocity shift close to 20% was obtained from a multilayered sensing structure of TbCo<sub>2</sub>/FeCo/LiNbO<sub>3</sub> for the shear horizontal wave mode as a ratio close to 1 between magneto-elastic film thickness and wavelength [14]. Recently, high frequency sensitivities of 8.3 kHz/mT, 17.72 kHz/mT and 21.17 kHz/mT

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**TABLE 1.** The sputtering process parameters for FeCo thin-film deposition.

Parameters	Values
Sputtering gas	Ar <sub>2</sub> with a purity of 99.9%
Sputtering pressure	1 Pa
Back pressure	$1 \times 10^{-5}$ Pa
Target-base distance	50 mm
Coating time	15 min
Sputter power	80 W
Heat treatment temperature	623 K
Excitation current	2 A

were achieved from the patterned FeCo thin-film coated SAW devices operating at 150 MHz [15]–[17].

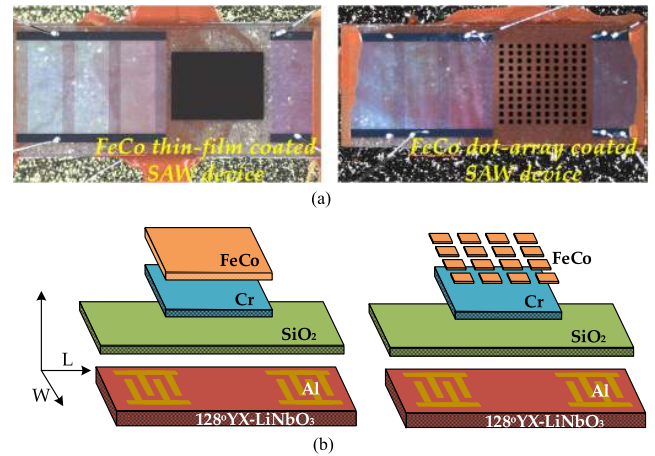
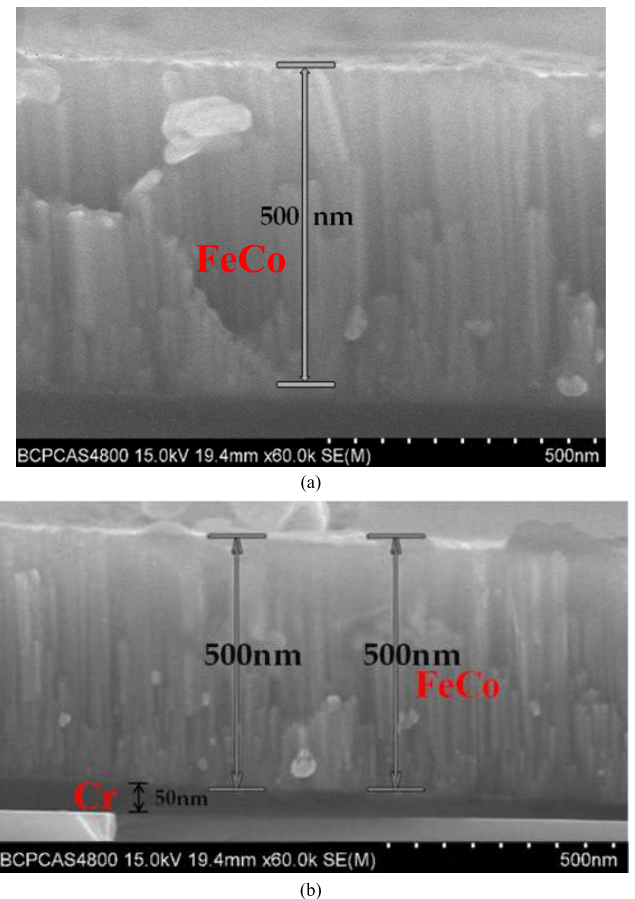
However, the mechanical nature of in magnetostriction makes the magnetostrictive thin-film suffering from significantly mechanical fatigue, which was overlooked in previous studies. To address the fatigue phenomenon of magnetostrictive thin-film in service, some specific experiments were conducted in this work by characterizing proposed FeCo thin-film coated SAW devices, and corresponding coping way was advised, that is, a design of dotted-pattern with Cr transition layer was proposed to build the SAW based magnetic-device, the magnetic-sensitivity and fatigue were improved effectively.

## II. SENSING DEVICE PREPARATION

A SAW based sensing device with a delay line pattern was developed on 128°YX LiNbO<sub>3</sub> piezoelectric wafer by using the standard photo-lithographic technique. High velocity of 3492 m/s and larger piezoelectric coefficient of ~5% were exhibited in LiNbO<sub>3</sub> wafer. The operation frequency of the sensing device was set to 150 MHz. Single phase unidirectional transducers (SPUDTs) were used to structure the two 300 nm Al-transducers to feature low insertion loss [18]–[20]. Corresponding electrode widths in SPUDTs were designed to ~3  $\mu$ m and 6  $\mu$ m. After the Al electrodes preparation, a SiO<sub>2</sub> thin-film (50 nm) was coated onto the device surface by utilizing the PECVD to protect the electrode in process of FeCo thin-film deposition.

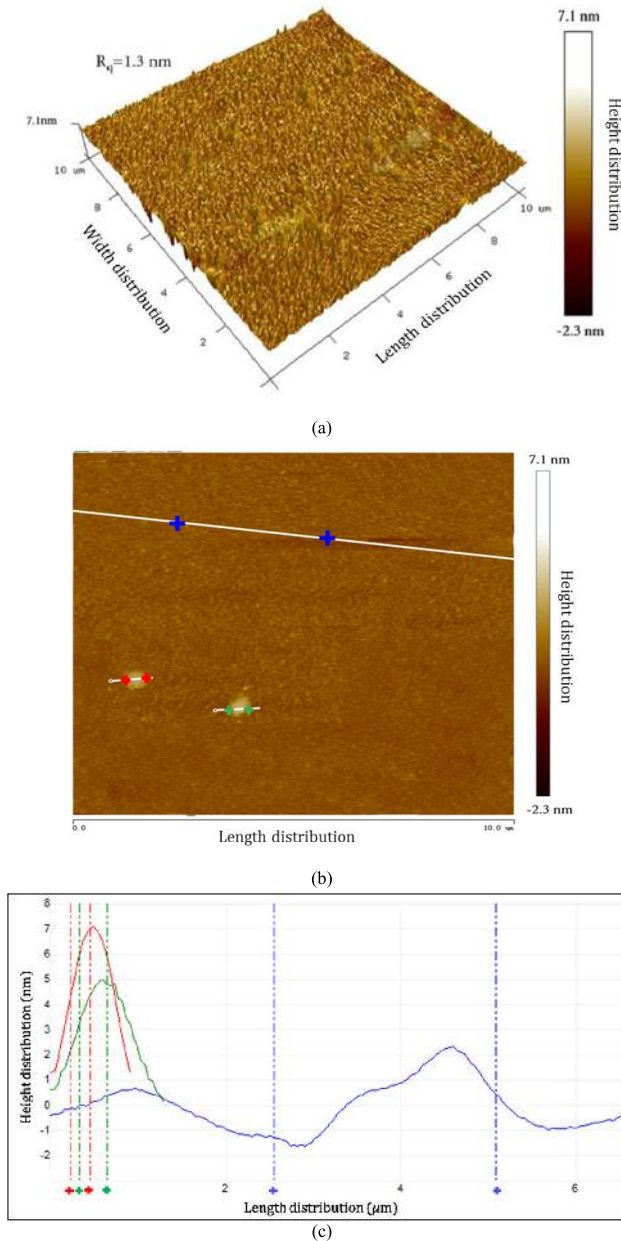
Then, a 500 nm FeCo thin-film was sputtered on top of the cleaned SAW devices [21], [22]. The Corresponding magnetron sputtering parameters are listed in Table. 1. For comparison, four different sensing devices were prepared, that is, FeCo thin-film coated device, FeCo/Cr thin-film device, FeCo dot-array coated device, and FeCo/Cr dot-array coated device. The dotted-pattern was conducted by employing the overlay process, and corresponding array interval was set to  $3\lambda \times 4\lambda$  ( $\lambda$  defines the wavelength). 50 nm Cr thin-film was deposited as the transition layer prior to FeCo thin-film deposition.

Fig. 1 (a) and (b) showed their photographs and schematic drawings of the prepared sensing devices, respectively.

**FIGURE 1.** (a) Photographs and (b) schematic drawings of prepared sensing devices coated with FeCo thin-film and FeCo dot-array.**FIGURE 2.** The cross-sectional morphology of (a) FeCo thin-film and (b) FeCo/Cr thin-film.

Clear FeCo thin-film and dot-array were observed between the transducers of the delay line configurations. Fig. 2 denotes the cross-sectional morphology of FeCo and Cr transition layer, and corresponding thicknesses are measured as ~500 nm and ~50 nm, respectively.

Also, the 2D and 3D atomic force microscope (AFM) characterization was conducted to the FeCo thin-film as depicted



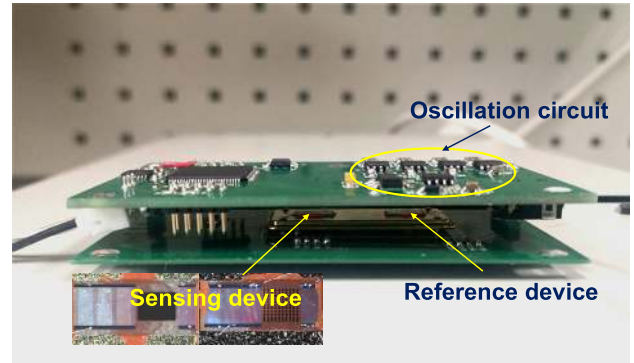
**FIGURE 3.** The (a) 2D and (b) 3D AFM characterization of the FeCo thin-film surface, and (c) the height distribution curves.

in Fig. 3, and the three height distribution curves of sections marked in the 2D AFM are shown in Fig. 3 (c). The surface height distribution of the line marked by the two red '+' in Fig. 3 (b) corresponds to the red curve in 3 (c), which are the same for green and blue markers. The film surface is relatively flat and smooth, and the corresponding surface average roughness  $R_q$  is evaluated as  $\sim 1.3$  nm.

### III. EXPERIMENTS AND DISCUSSIONS

#### A. EXPERIMENTAL SETUP

The proposed sensing device was packaged and connected into the differential oscillation loop depicted in Fig. 4.



**FIGURE 4.** The sensing circuit with packaged sensing devices.

**TABLE 2.** Average magnetic-sensitivity and hysteresis error of four type sensing devices.

Sensor type	Average magnetic sensitivity ( the first 5 tests) (kHz/mT)	Average hysteresis error ( the first 5 tests)	Average magnetic sensitivity (100 cyclic tests) (kHz/mT)
FeCo thin-film	6.16	4.72%	3.96
FeCo/Cr thin-film	3.72	1.21%	3.27
FeCo dot array	10.7	0.85%	2.31
FeCo/Cr dot array	5.35	0.69%	5.13

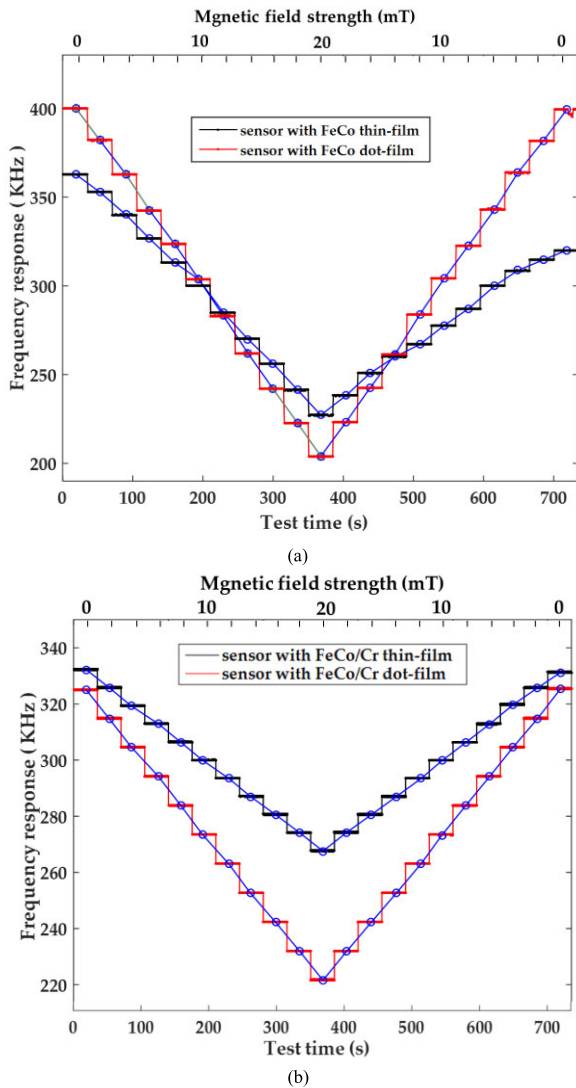
The mixed frequency signal differenced by the naked device (reference device) was collected as sensing signal to feature excellent temperature compensation. Then, using the Helmholtz coil system [23], the proposed sensing devices were characterized, and the fatigue phenomenon was demonstrated experimentally.

#### B. SENSITIVITY EVALUATION

The typical sensor responses of proposed sensing devices in the first few cyclic tests were pictured in Fig. 5. The x-axis denotes the test time and varied magnetic field intensity (from 0 to 20 mT and 20 mT to 0) with interval of 2 mT. The corresponding average magnetic-sensitivity and hysteresis error in the first 5 tests were concluded in Table 2. Each applied magnetic field intensity was kept for  $\sim 30$  seconds, and corresponding mean value was collected and denoted by the circles 'o' in Fig. 5 to describe the frequency response. Obviously, the FeCo dot-array coated device features higher magnetic-sensitivity and lower hysteresis error. The reason lies in the release of coercive force and enhancement of the magnetostrain in FeCo thin-film by the patterned design. However, the existence of Cr transition layer weakens the magnetostrain transfer, and lowered the magnetic-sensitivity.

To explore the reasons, the hysteresis loops and magnetostrictive curves of the four prepared sensing devices were measured by using the alternating gradient magnetometer (model AGM2900-04C), as shown in Fig. 6. It indicates that the coercive ( $H_c$ ) and magnetostrictive coefficient ( $\beta$ ) of thin-film and dot-array was reduced after adopting the Cr transition layer, that is,  $H_{c-FeCothin-film}(126.2 \text{ Oe}) > H_{c-FeCo/Crthin-film}(101.5 \text{ Oe}) > H_{c-FeCodot-array}(97 \text{ Oe}) > H_{c-FeCo/Crdot-array}(85.7 \text{ Oe})$ ,  $\beta_{FeCodot-array}(119.3 \text{ ppm}) >$



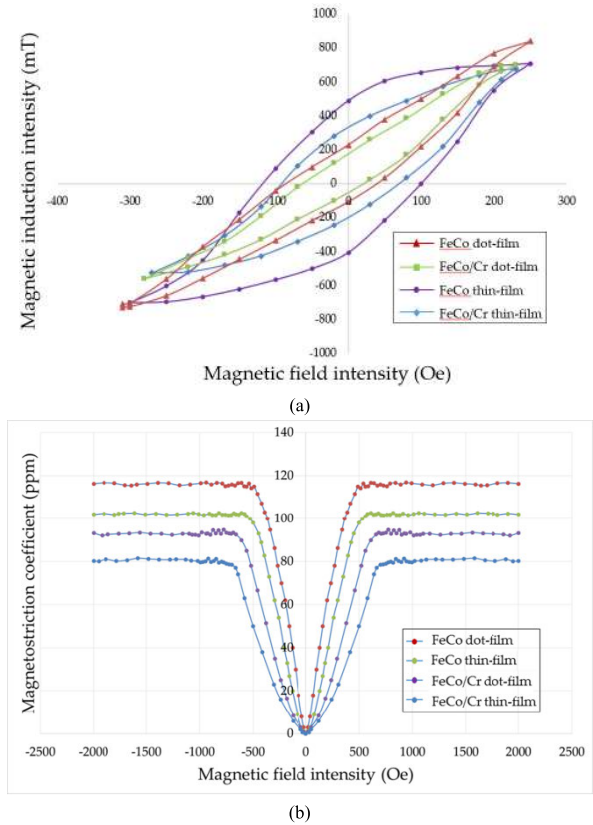


**FIGURE 5.** The measured sensor responses from the proposed SAW devices coated with (a) FeCo thin-film and FeCo dot array, (b) FeCo/Cr thin-film and FeCo/Cr dot array.

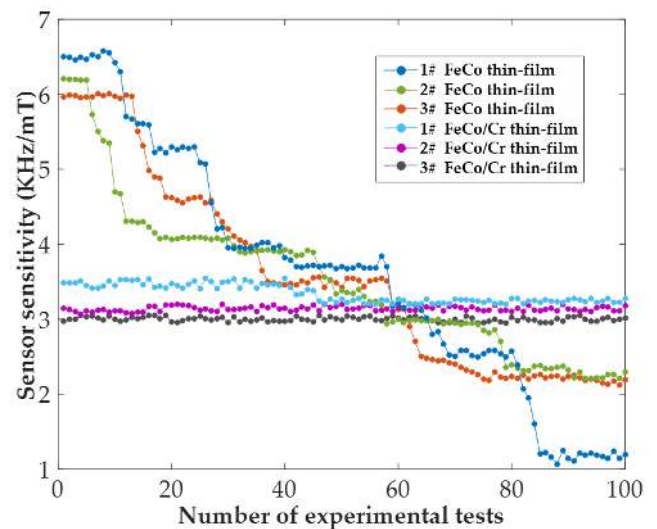
$\beta_{\text{FeCo thin-film}} (102.6 \text{ ppm}) > \beta_{\text{FeCo/Cr dot-array}} (92.1 \text{ ppm}) > \beta_{\text{FeCo/Cr thin-film}} (80.2 \text{ ppm})$ , thereby explaining the decrease in hysteresis error and magnetic-sensitivity of the sensors with Cr transition layer. Additionally, the FeCo dot-array enhances significantly the magnetic-sensitivity and reduces the hysteresis error over the FeCo thin-film, which is the result of enlarged magnetostrictive properties and reduced coercivity in the FeCo dots.

### C. FATIGUE ANALYSIS OF FECo THIN-FILM COATED DEVICES

There may be significantly invalidation in magnetostrictive thin-film because of the fatigue phenomenon arisen by the magnetostriction behaviors. To demonstrate the fatigue phenomenon, 100 cyclic testing runs were conducted on three sets of devices deposited FeCo thin-film and FeCo/Cr thin-film (marked with #1, #2, #3) with a 10-minute interval.

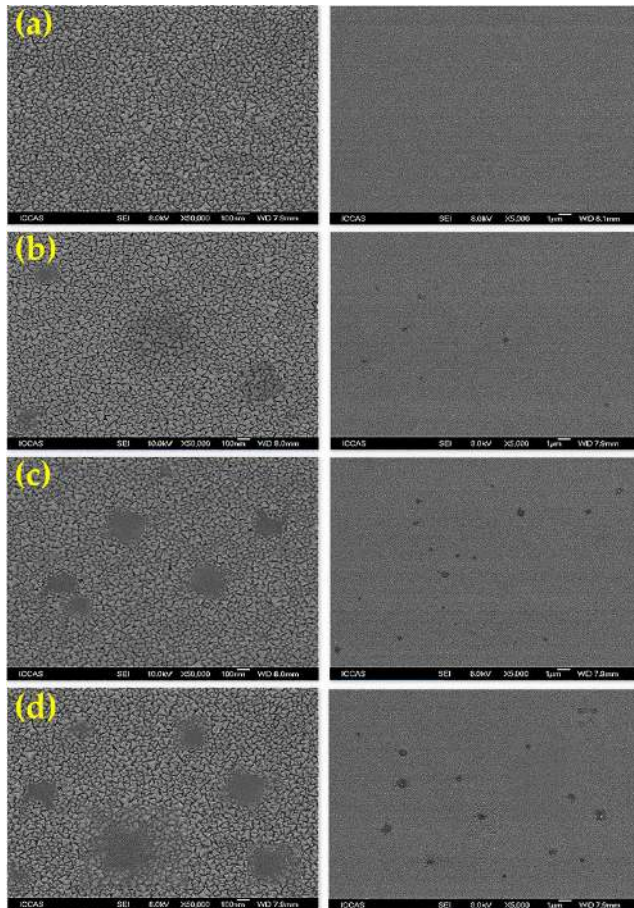


**FIGURE 6.** (a) The measured hysteresis loops and (b) magnetostrictive curves of FeCo thin-film, FeCo/Cr thin-film, FeCo dots and FeCo/Cr dots.



**FIGURE 7.** The measured relationship of magneto-sensitivity and cyclic testing runs from the FeCo thin-film coated sensing devices.

Figure 7 denotes the relationship between their magneto-sensitivity and cyclic testing runs. With increases in cyclic testing runs, a marked decline was observed in the magneto-sensitivity of FeCo thin-film coated devices. Interestingly enough, the alleviation in decays of magneto-sensitivity was observed when Cr thin-film was employed. It is obvious that the Cr thin-film contributes well to adhesion of FeCo

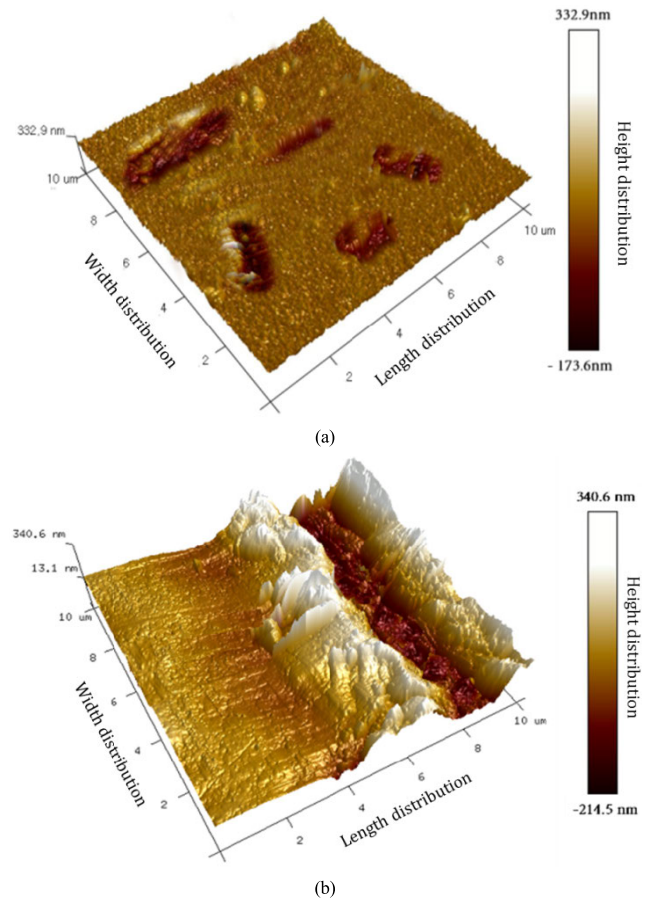


**FIGURE 8.** The surface morphologies of the 1# FeCo thin-film in cyclic testing runs, (a) 0, (b) 30, (c) 60 and (d) 100 runs.

thin-film to the substrate, and suppresses the fatigue in FeCo thin-film.

Corresponding evidences are given by the SEM pictures of FeCo thin-film in cyclic testing. The unloaded 1# FeCo thin-film was pictured in Fig. 8 (a), and the surface morphologies after 30, 60, and 100 cyclic testing runs are depicted in Fig. 8 (b-d). As the cyclic testing runs increases, the obvious destruction in FeCo thin-film indicated by the black areas in the picture gradually increased. The reason lies in the magnetostrictive strain in FeCo film interacts mechanically with the substrate continuously, resulting FeCo thin-film shedding from the substrate in service.

The more credible evidence was produced by the AFM pictures of the FeCo thin-film, as shown in Fig. 9. Compared with the AFM picture of the unloaded 1# FeCo thin-film in Fig. 3(a), several distinct irregularities of “pits” with height equivalent to 1# FeCo film thickness were observed after 15 cyclic testing runs (Fig. 9(a)), that is caused by the uneven force in the film arisen from multiple magnetostriction, leading to a slump in magnetic-sensitivity. Fig. 9(b) denotes clear ridge shapes with height of 555.1 nm originated from the stretching strain in FeCo thin-film after multi-testing, and this leads to fall off and cracks of the thin-film [24], [25].



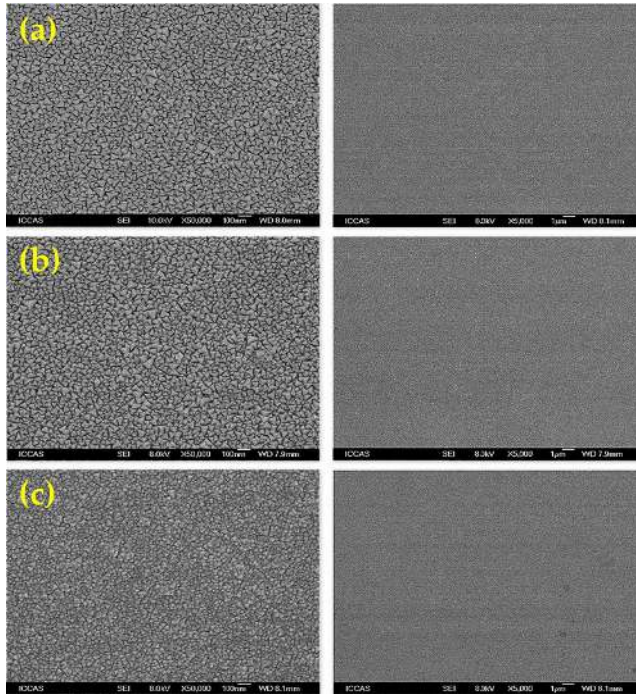
**FIGURE 9.** The surface morphologies of the 1# FeCo thin-film after 15 cyclic testing runs: (a) pits and (b) cracks.

The Cr thin-film has altered thing somewhat. As we can see, the SEM pictures of the FeCo surface after 30, 60, and 100 cyclic testing runs from the 1# FeCo/Cr thin-film coated devices were offered in Fig. 10. The thin-film surface keeps perfect uniform, and there are almost no any cracks or protrusions observed in the FeCo film. Obviously, the Cr thin-film enhances effectively the adhesion of the FeCo film on the substrate, and weakens the mechanical fatigue in the magnetostrictive thin-film. But, it is at the expense of sensitivity because of the weakened magnetostriction behavior.

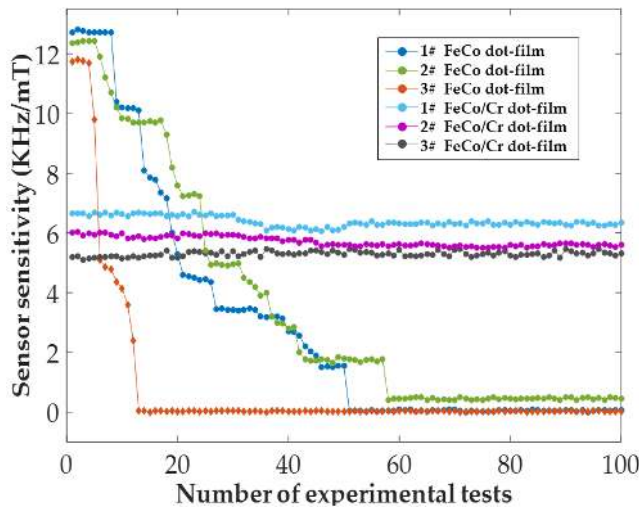
#### D. FATIGUE ANALYSIS OF FECo/CR DOT-ARRAY COATED DEVICES

As mentioned in Fig. 11, 100 cyclic testing runs were performed on three sets of devices deposited (marked with #1, #2, #3) FeCo dot array and FeCo/Cr dot array. The dotted-pattern on magnetostrictive thin-film improves well the magneto-sensitivity, and larger sensitivity value of  $\sim 12$  kHz/mT was achieved from the FeCo dot-array coated device in the first few tests. However, it also suffers from the mechanical fatigue, with the increase of testing runs, a sharp drop in sensitivity was observed. This illustrates more serious shedding arisen from stretching strain in FeCo dots. Moreover, the measured results from the FeCo/Cr dot-array coated





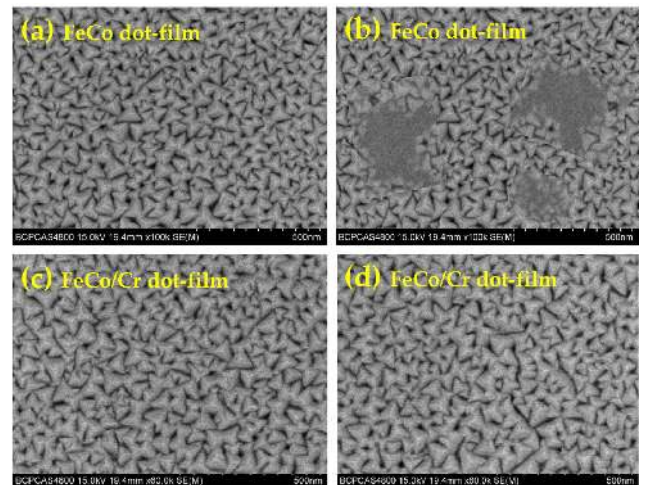
**FIGURE 10.** The surface morphologies the 1# FeCo/Cr thin-film in cyclic testing runs, (a) 30, (b) 60, and (c) 100 runs.



**FIGURE 11.** The measured relationship of magneto-sensitivity and cyclic testing runs from the FeCo dot-array coated sensing devices.

devices were in marked contrast to that from the devices with FeCo dot-array. The magneto-sensitivity was very steady in the testing runs ( $\sim 6$  kHz/mT).

Moreover, Fig. 12 shows the SEM pictures of the 1# FeCo dot-array and 1# FeCo/Cr dot-array in cyclic testing runs, respectively. Obvious destruction in the FeCo dot-array was observed, and instead, the FeCo/Cr dot-array surface keeps perfect uniform. It means the mechanical fatigue was alleviated significantly because of the adhesion improvement by employing the Cr-transition layer. The average sensitivities in 100 cyclic testing runs of the prepared sensing devices were also concluded in Table 2. Larger average sensitivity was



**FIGURE 12.** The surface morphologies of the 1# FeCo dot-array and 1# FeCo/Cr dot-array in cyclic testing runs, (a), (c) 0 and (b), (d) 60 runs.

achieved from the FeCo/Cr dot-array coated devices. Hence, patterned design and transition layer were advised to build the SAW magnetic sensing devices to achieve high sensitivity and excellent stability.

#### IV. CONCLUSION

In this paper, the mechanical fatigue of FeCo thin-film coated SAW devices for sensing magnetic field was investigated. Experimental results indicate that obvious shedding are observed from the FeCo thin-film after cyclic testing, as the result, a slump occurs at the magneto-sensitivity after cyclic testing runs. Interestingly, it can be improved by employing the Cr transition layer. There are almost no shedding in the optical observation, and only slightly shift in magnetic-sensitivity in cyclic testing. It means the Cr transition layer improves well the adhesion of the FeCo thin-film. But a downside is at expense of magneto-sensitivity. The reason lies in the reduced magnetostrictive coefficient and the limitation of the magnetostrain-transfer in FeCo thin-film to substrate, and corresponding interaction with the SAW propagation was weakened. To address such issues, a dotted-pattern and Cr transition layer was proposed for building SAW based magnetic-device, high magnetic-sensitivity and good fatigue were achieved in the experiments.

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and provincial-level scientific research projects, and has published more than 20 articles.



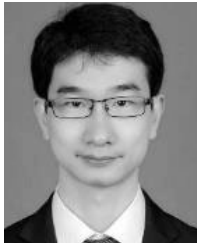
Distinguished Professor at IOA, Chinese Academy of Science, China. His current research involves SAW sensors. Until now, he has published more than 200 academic articles, and has applied for 40 invention patents. Moreover, he won the "Experienced Researcher" title awarded by the Humboldt Foundation, Germany, and "100 talents Plan" of the Chinese Academy of Sciences.



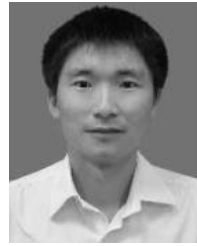
**YUAN SUN** received the bachelor's degree from Central South University, in 2017. She is currently pursuing the Ph.D. degree with the Laboratory of Ultrasound Technology Center, Institute of Acoustics (IOA), Chinese Academy of Sciences. She is mainly engaged in SAW current sensor technology research.



**MENGWEI LIU** received the Ph.D. degree from the Dalian University of Technology, in 2006. From 2006 to 2009, she has worked as a Postdoctoral Researcher at the Laboratory of Ultrasound Technology Center, Institute of Acoustics (IOA), Chinese Academy of Sciences, where she is currently a Professor. She is mainly engaged in the research of acoustic microsensor and signal processing devices and systems, carried out the research and development of piezoelectric micro-force sensor, piezoelectric/capacitive micro-microphone, Lamb wave bio-chemical sensor, piezoelectric thin film bulk acoustic resonance, surface acoustic wave sensor, and signal processor. Until now, she has published about 60 academic articles, and has applied for ten invention patents.



**XUFENG XUE** received the M.S. degree from Beijing Normal University, in 2013. Since 2013, he has been an Assistant Researcher with the Institute of Acoustics (IOA), Chinese Academy of Sciences, China. His current research involves the signal processing of SAW sensors. Until now, he has published more than ten academic articles, and has applied for five invention patents.



**ZHAOFU DU** received the M.S. degree from Lanzhou University, in 2004, and the Ph.D. degree from the Central Iron and Steel Research Institute, in 2013. He has been with the Central Iron and Steel Research Institute, and as a Visiting Scholar at the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, from 2014 to 2015. His current research involves magnetic materials and energy materials. He has published more than 20 articles and has applied for more than ten invention patents.



**YONG LIANG** received the bachelor's degree from the Department of Physics, Capital Normal University. Since July 1997, he has been with the Acoustic MEMS Laboratory, Institute of Acoustics (IOA), Chinese Academy of Sciences, as an Assistant Engineer, where he is currently an Engineer.



**JINGTING LUO** received the Ph.D. degree from Tsinghua University, in 2012. From 2012 to 2016, he was an Assistant Professor with the College of Physics and Technology, Shenzhen University, Shenzhen, China. From 2016 to 2017, he was an Academic Visitor with the Faculty of Engineering and Environment, University of Northumbria, Newcastle, U.K. Since 2017, he has been an Associate Professor with the College of Physics and Optoelectronic Engineering, Shenzhen University.

He has extensive experience in thin-film/materials, lab-on-chip, micromechanics, piezoelectric thin films, nanostructured composite/films for applications in MEMS, as well as sensing and energy applications. He has published over 100 Science Citation Index (SCI) journal articles and over 20 conference papers. His current SCI H-index is 34. He is a regular journal paper reviewer for more than 10 journals, and has co-organized five conferences. He is currently the Secretary of the Shenzhen Vacuum Society and a Committee Member of the Chinese Vacuum Society.

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