Thin-Film Active Nano-PWAS for Structural Health Monitoring

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ABSTRACT

Structural health monitoring (SHM) is an emerging field in which smart materials interrogate structural components to predict failure, expedite needed repairs, and thus increase the useful life of those components. Piezoelectric wafer active sensors (PWAS) have been previously adhesively-bonded to structures and demonstrate the ability to detect and locate cracking, corrosion, and disbonding through use of pitch-catch, pulse-echo, electro/mechanical impedance, and phased array technology. The present research considers structurally-integrated PWAS that can be fabricated directly to the structural substrate using thin-film nano technologies (e.g., pulsed-laser deposition, sputtering, chemical vapor deposition, etc.) Because these novel PWAS are made up of nano layers they are dubbed nano-PWAS. Nano-PWAS research consists of two parts, thin-film fabrication and nano-PWAS construction. The first part is how to fabricate the piezoelectric thin-film on structure materials. In our research, ferroelectric BaTiO₃ (BTO) thin films were successfully deposited on structure material Ni and Ti by pulsed laser deposition under the optimal synthesis conditions. Microstructural studies revealed that the as-grown BTO thin films have the nanopillar structures and the good interface structures with no inter-diffusion or reaction. The dielectric and ferroelectric property measurements exhibit that the BTO films have a relatively large dielectric constant, a small dielectric loss, and an extremely large piezoelectric response with a symmetric hysteresis loop. The second part is nano-PWAS construction and how they are related to the active SHM interrogation methods. Nano-PWAS architecture achieved through thin-film deposition technology and its potential application for SHM were discussed here. The research objective is to develop the fabrication and optimum design of thin-film nano-PWAS for structural health monitoring applications.

Keywords: thin-film, nano-PWAS, pulsed laser deposition, structural health monitoring

1. INTRODUCTION

1.1 Background

Structural health monitoring (SHM) is a method of determining the health of a structure from the readings of an array of permanently-attached sensors that are embedded into the structure and monitored over time. SHM can be performed in basically two ways, passive and active. Passive SHM consists of monitoring a number of parameters (loading stress, environment action, performance indicators, acoustic emission from cracks, etc.) and inferring the state of structural health from a structural model. In contrast, active SHM performs proactive interrogation of the structure, detects damage, and determines the state of structural health from the evaluation of damage extend and intensity. Both approaches aim at performing a diagnosis of the structural safety and health, to be followed by a prognosis of the remaining life. Passive SHM uses passive sensors which only “listen” but do not interact with the structure. Therefore, they do not provide direct measurement of the damage presence and intensity. Active SHM uses active sensors that interact with the structure and thus determine the presence or absence of damage. The methods used for active SHM resemble those of nondestructive evaluation (NDE), e.g., ultrasonics, eddy currents, etc., only that they are used with

embedded sensors. Hence, the active SHM could be seen as a method of embedded NDE. One widely used active SHM method employs piezoelectric wafer active sensors (PWAS US 7, 024, 315 B2, USCRF 00330), which send and receive Lamb waves and determine the presence of cracks, delaminations, disbonds, and corrosion. Due to its similarities to NDE ultrasonics, this approach is also known as embedded ultrasonics.

1.2 Motivation

Piezoelectric wafer active sensors have been proven a valuable tool in structural health monitoring. Piezoelectric wafer active sensors are able to send and receive guided Lamb/Rayleigh waves that scan the structure and detect the presence of incipient cracks and structural damage. These inexpensive and unobtrusive active sensors can be used in many applications spanning from aerospace to civil infrastructure. However, the current methods for fabrication and installation of these sensors on metallic structures are rather “primitive”: pre-manufactured piezoelectric wafers are adhesively bonded to the structural surface. The bonding layer is susceptible to environmental ingress that may lead to loss of contact with the structural substrate. The bonding layer may also induce acoustic impedance mismatch with detrimental effects on damage detection. To overcome these shortcomings we used ferroelectric thin film nano technology to produce the active nano-PWAS directly on the structural substrate using nanofabrication technology.

2. STATE OF THE ART

In recent years, considerable progress has been achieved in developing NDE methods that actively interrogate the structure using guided Lamb and Rayleigh waves^{[1]-[5]}. However, conventional NDE transducers are relatively large and expensive; for SHM applications, smaller and inexpensive active sensors are needed. Recent SHM work^{[6]-[10]} has shown that piezoelectric wafers adhesively bonded to the structure may successfully emulate the NDE methodology (pitch-catch, pulse-echo, phased array) while being sufficiently small and inexpensive to allow permanent attachment to the monitored structure.

However, the current methods for fabrication and installation of these sensors on engineering structures are rather “primitive”: pre-manufactured piezoelectric wafers are adhesively bonded to the structural surface. The bonding layer is susceptible to environmental ingress that may lead to loss of contact with the structural substrate. The bonding layer may also induce acoustic impedance mismatch with detrimental effects on damage detection. Not surprisingly, several unresolved fundamental issues impede its development towards industrial acceptance and implementation:

1. **Unacceptable durability and survivability** of adhesively-mounted piezoceramic wafers
2. **Large power and voltage requirements** due to poor efficiency of piezoceramic wafers
3. **Excessive variability and uncertainty** in functional properties due to manual installation methods, which are labor intensive and subjected to extensive human error
4. **Inability to utilize advanced sensor architectures** due to the use of bulk piezoceramics
5. **Unsuitable for efficient wireless interrogation** due to the inherent limitations of the basic approach

Figure 1 (a) pitch-catch method; (b) pulse-echo method; (c) bonded interface between PWAS and structure

The research objective is to develop the fabrication and optimum design of piezoelectric thin-film nano-PWAS for structural health monitoring applications. This interdisciplinary research crosses the engineering and science boundaries and addresses the problem in a coordinated approach focused on understanding the fundamentals aspects of fabricating and using thin-film active sensors on typical structural materials.

3. THIN FILM FABRICATION AND CHARACTERIZATION

Thin-film active nano-PWAS research consists of two parts, thin-film fabrication and nano-PWAS construction. The first part is how to fabricate the piezoelectric thin-film on structures. Ferroelectric BaTiO₃ (BTO) thin films were successfully deposited on Ni tape and Ti plate by pulsed laser deposition under the optimal synthesis conditions. Recently, Chen at UTSA has developed a unique technique for the first time to achieve in-situ fabrication of BTO thin films on the typical structural material Ni and Ti using pulsed laser deposition technique. Interface engineered nano technique was developed to control the interface structures and the film quality. The interfaces between the BTO films and substrates were found to be with/without a buffer layer NiO that was usually formed during the deposition of metal on oxygen or oxide materials at high temperature. BaTiO₃ thin films were deposited on Ni and Ti substrates in a PLD system using a KrF excimer laser with a wavelength of 248 nm with an energy density of about 2.5 J/cm² and a laser repetition rate of 5Hz. The BTO thin films were fabricated with various conditions, details can be found from the literatures^{[15],[16]}. X-ray diffraction (XRD) was employed to understand the crystal phases and the transmission electron microscopy (TEM), plan-view and cross-section, were employed to study the microstructure of the as-grown films and interfacial layers. The dielectric properties were characterized by using a Radiant RT6000 for understanding the physical properties of the as-grown films.

3.1 BaTiO₃ thin films on Ni tape

Figure 2 shows the as-deposited BTO thin film on Ni with NiO buffer layer. A layer of NiO with its thickness of 80 nm was synthesized via in situ oxidation treatment of the Ni tape in oxygen atmosphere of 300 Torr at 800°C for 3 min. NiO is rock salt structure with good electrical conductivity, which can be used as conductive electrodes and avoiding the formation of a dead layer formed between the ferroelectric film and metal substrate. It should be pointed out that the rock salt structural NiO has good crystallographic compatibility to the perovskite microstructure of BTO growth.

Figure 2 (a) plan-view and (b) Cross-section TEM image of the BTO films on Ni with NiO interlayer. Inset is SAED pattern

Jiang from UTA conducted a thorough and systematic microstructure and interface analysis of the structurally integrated thin film sensors. The effect of the processing conditions on the quality of the sensors and its interface with respect to the substrate was investigated, which can be used for optimizing the processing condition to achieve the high quality film sensors and strong sensor/substrate bonding. Microstructure studies suggest that the films have polycrystalline nanopillar structures with an average size of approximately 90 nm as revealed by plan-view and cross-section transmission electron microscopy (TEM). The size of the grains in Figure 2(a) varies from 35 nm to 160 nm in diameter, while the majority grains have a size of about 90 nm in diameter. The inset SAED pattern of the film shows sharp diffraction rings, indicating that all the grains are in plan randomly oriented. The structure of the as-grown BTO film was identified as a tetragonal structure with a space group of $p4mm$ and lattice parameters of $a=3.992\text{\AA}$ and $c=4.036\text{\AA}$. For example, the inner 6 diffraction rings 1, 2, 3, 4, 5 and 6 have a lattice spacing of 4.0 Å, 2.8 Å, 2.3 Å, 2.0 Å, 1.8 Å, 1.64 Å and 1.4 Å, respectively, which can be identified as the (001), (101), (111), (002), (102) and (112) reflection of the tetragonal BTO. Figure 2 (b) is a cross-sectional TEM image showing the interface structures of the BTO films on NiO buffered Ni tapes and the inset is the low magnification image of the films. The BTO film has a thickness of about 500 nm and consists of nanopillar structures. Most of the nanopillars extend from the film/substrate interface to the film surface with a length of about 500 nm and show a lateral dimensions from 30 nm to 100 nm (inset),

which is close to the value obtained from the plan-view TEM. An intermediate layer that can be identified as NiO was observed between the BTO film and Ni substrate (Figure 2b) indicating that a NiO oxidized layer was successfully produced prior to the deposition of BTO film. The BTO film is found to be very well bound the NiO layer with a sharp interface in between. The NiO layer has a thickness of about 80 nm and a clear interface with respect to the Ni substrate.

The ferroelectric BTO films can be directly grown on the nano Ni surface without the NiO interlayer by nano fabrication technique. As seen in Figure 3 (a), a cross-sectional TEM image shows the interface structure of the BTO films on Ni tapes. The BTO film has a thickness of about 200 nm and consists of nanopillar structures with lateral dimensions of about 100 nm, which is close to the value obtained from the plan-view TEM. The intermediate (IM) layer between the BTO film and Ni substrate shows nanocrystalline structure. Figure 3(b) is a plan-view TEM image and the SAED pattern (inset) of the IM layer. The grain size of the nanostructures varies from 30 to 100 nm in diameter and is smaller than that of the BTO grains. The nanostructures in the IM layer were found to be pure Ni ($a = 3.52 \text{ \AA}$) as identified by the electron diffraction analysis. For example, diffraction rings 1, 2, 3 and 4 have a lattice spacing of $2.03 \text{ \AA}$, $1.76 \text{ \AA}$, $1.25 \text{ \AA}$ and $1.06 \text{ \AA}$, respectively, which can be identified as the (111), (200), (220) and (311) reflection of Ni. More than 60% of the nanopillars in the films possess the same orientation with the a -axis lying in the film plane and the [011] axis perpendicular to the film plane. This great achievement suggests that the BTO films directly on Ni tape with no NiO layer has paved a way to develop supercapacitance devices for the energy harvest applications.

Figure 3 (a) Cross-section and (b) plan-view TEM image of the BTO films on Ni with no NiO interlayer. Inset is SAED pattern.

X-ray diffraction $\theta - 2\theta$ scan (XRD) were employed to characterize the microstructures and crystallinity of the as-grown BTO films. As seen in Figure 4 (a), the XRD pattern from the as-deposited BTO thin film on Ni shows all the peaks from the polycrystalline BTO phases and Ni substrate. These peak positions suggest that the Ni substrate is cubic phase and the BTO film belongs to the tetragonal phase. This indicates that the BTO film has randomly oriented grains. Figure 4 (b) is the XRD $\theta - 2\theta$ pattern from the as-deposited BTO thin film on Ni without NiO buffer. The relative stronger intensity from the (200) diffraction in the BTO film indicates that the BTO film has a slightly preferred c-axis oriented rather than a randomly oriented grains.

The impact of the microstructure difference on the physical properties can be clearly seen from the PRM image of the films (Figure 4 (c) and (d)). The films with orientation preferred structures possess nearly the same polarization direction over 60% areas. The dielectric and ferroelectric property studies demonstrated that such BaTiO_3 films on Ni substrate exhibit a very high resistivity value of $10^{10} \Omega\text{cm}$.

The ferroelectric property measurements were also performed at room temperature, as seen Figure 5. It is surprisingly found that the as-grown BTO films on Ni metal tapes with a NiO buffered layer exhibit very high resistivity value of $10^{10} \Omega\text{cm}$. The ferroelectricity of the BTO films was evidenced from the hysteresis loop. The room temperature spontaneous polarization, remnant polarization, and coercive field from the as-deposited BTO layer can be obtained to be about $2.0 \mu\text{C}/\text{cm}^2$ and $1.0 \mu\text{C}/\text{cm}^2$, respectively, with a coercive field of $25 \text{ kV}/\text{cm}$. It is known that the lattice dipole along the c-axis for a tetragonal perovskite structure is the origin of the ferroelectric properties associated with BTO. In other words, the ferroelectric dipole originates from ionic displacement in the c-axis direction, only c-axis oriented BTO thin films exhibit ferroelectricity. The a-axis oriented BTO film cannot show ferroelectric hysteresis due to the randomly oriented polarization, the large spontaneous polarization obtained in the as-deposited film is consistent

with the result of the microstructure measurement that the film has highly c-axis oriented texture structure. The piezoelectric response of the as-deposited BTO film was surprisingly found to be $130 (\times 10^{-12} \text{ C/N})$ which is about 30% larger than the values ($90 - 100 \times 10^{-12} \text{ C/N}$) of BTO single crystalline and polycrystalline bulk materials. The large piezoelectric response might result from the uniform nanodomain structures. The use of Ni substrate and alloys with Ni buffer layer offer better crystallinity of thin films according our preliminary results. However, despite the widespread application of PLD, the epitaxial quality and the microstructures of the as-grown oxide thin films are highly dependent upon the synthesis conditions and the selected materials. Stoichiometric films can only be synthesized under certain processing conditions (temperature, pressure, incident beam energy density, etc.).

Figure 4: (a) X-ray diffraction θ - 2θ scans of randomly oriented BTO/NiO/Ni thin film; (b) X-ray diffraction θ - 2θ scans of oriented BTO/Ni thin film; (c) PRM images of the films with randomly oriented BTO/NiO/Ni; (d) orientation preferred BTO/Ni nanostructures.

Bhalla and Guo at UTSA have recently developed by a novel characterization technique, scanning electron acoustic microscopy (SEAM). It has the resolution of an electron microscope but penetration depth one to two orders of magnitude larger. (The penetration depth is adjustable using acoustic signal modulation.) SEAM is based on the detection of electron acoustic (EA) signals that are generated by heating with a pulsed electron beam modulated by a driving electric signal applied on a beam blaker in a scanning electron microscope (SEM) column. The propagated EA signal is sensed by a piezoelectric transducer in contact with the specimen. Through computer controlled scan and amplification, the SEAM images are formed for a particular depth of penetration, as a function of modulation frequency. SEAM has been used successfully in the study of ferroelectric ceramics, semiconductors, magnetic materials, and many others. It has the advantage of permitting a micro structural view into the bulk of a small sample.

This is in contrast to X-ray diffraction and SEM examinations that give only information on the surface regions. This newly developed technique seems ideally suited to provide both the needed resolution and the in-depth imaging capability in the real state of the sensor deposited on the substrate.

Figure 5: Dielectric property showing the hysteresis loop achieved on the ferroelectric BaTiO₃ thin films on (a) Ni and (b) Ti.

3.2 BaTiO₃ thin films on Ti plate

BaTiO₃ films on the Ti substrates fabricated using PLD by modifying the growth conditions have also been studied. BaTiO₃ films are composed of crystalline nanopillars with good interface structures with respect to the Ti substrates (Figure 6). The grain size of the BaTiO₃ nanopillars and their interface structures between the film and Ti were found to strongly depend on the fabrication conditions. BaTiO₃ thin films composed of randomly oriented and orientation preferred nanopillars with a grain size varying from 50 nm to 200 nm were successfully fabricated. The BaTiO₃ films have a good interface and strong adhesion with respect to the Ti substrate through a grain sized gradient Rutile TiO₂ intermediate interfacial region.

Figure 7 is a $\theta - 2\theta$ XRD pattern of the as-deposited BTO thin film on Ti exhibiting peaks from BTO, Rutile TiO₂ and Ti. The BTO films on Ti were found to have the tetragonal structure with lattice constant $a = 4.00 \text{ \AA}$ and $c = 4.03 \text{ \AA}$. The rutile TiO₂ has a lattice constant $a = 4.61 \text{ \AA}$ and $c = 2.97 \text{ \AA}$. The Ti substrate has a structure of α -Ti and the lattice constant was found to be $a = 2.97 \text{ \AA}$ and $c = 4.78 \text{ \AA}$, which is about 1% larger than the lattice constant of pure Ti ($a = 2.95 \text{ \AA}$ and $c = 4.68 \text{ \AA}$). Such a lattice expansion might be understood as the induction of the O atoms into the Ti lattice.

Figure 6 BTO on Ti (a) Cross-section and (b) plan-view TEM image of the BTO films on Ti. Inset is SAED pattern of (b).

Figure 7 $\theta - 2\theta$ XRD pattern of the BTO films on Ti substrate

4. NANO-PWAS CONSTRUCTION

The second part of nano-PWAS architectures is nano-PWAS construction and how they are related to the active SHM interrogation methods. The novel approach makes the object of a recent US provisional patent and consists in using layered architecture in concern with guided wave SHM understanding and modeling to move from current single-layer PWAS to future multilayer nano-PWAS, as shown in Figure 8. The thin film technologies enable the development of several highly-efficient active sensors. The goal is to achieve wireless battery-less capability similar to the RFID tags ubiquitous in the commercial world. Here, there is a battery-less active sensor to be powered only by an interrogating microwave beam aimed at it from a standoff distance. The new sensors (dubbed “**nano-PWAS**” due to the thin-films nano size) concept is developed in incremental steps as follows:

- Single-layer thin-film nano-PWAS
- Multi-layer thin-film nano-PWAS
- Micro phased array of nano-PWAS transducers
- Wireless battery-less operation via tag antenna

Figure 8 Sequential development of the multi-layer battery-less nano-PWAS phased array

4.1 Single-layer thin-film nano-PWAS

The single-layer thin-film nano-PWAS consists of thin piezoelectric film directly deposited on a structural substrate with an electrode pattern deposited on top. The use of an interdigitated (IDT) electrode pattern that permit tuning in selected MHz frequencies, as appropriate to the size and type of structural damage that needs to be detected. Previous work has proven that the deposition of ferroelectric thin film on structural materials is feasible. The feasibility of constructing IDT electrodes on piezoelectric substrates and using them to energize surface acoustic waves (SAW) has also been tested. The IDT electrode approach was selected because it permits a better coupling with SAW and Lamb waves used in the damage detection process. Figure 9a shows an IDT electrode pattern fabricated on Dupont Pyralux copper-clad flexible laminate by photolithography technique. Each SAW type sensor in array consists of five pairs of electrodes. The electrode finger is 200 μ m width with 200 μ m space. The aperture of the device was 4 mm. The resonance of this SAW-type device was measured with an HP4194 impedance analyzer; the resonance frequency is

~5MHz (Figure 9b) is close to the design value. This method will be used to test single-layer thin-film nano-PWAS to be supplied by the UTSA team members.

4.2 Multi-layer nano-PWAS

The realization of a multi-layer thin-film construction is essential for the success of the nano-PWAS concept. This aspect can be easily illustrated through the following 1-D analysis of a piezo wafer with top and bottom electrodes: recall the linear piezoelectric equations for 31 coupling between the E_3 electric field and S_1 strain and T_1 stress, i.e.,

$$S_1 = s_{11}T_1 + d_{31}E_3 \quad (1)$$

Equation (1) expresses the strain in terms of two variables, the mechanical stress T_1 and the electric field E_3 . The part of the strain due to the piezoelectric effect, S_1^{piezo} , is obtained by making $T_1 = 0$, i.e.,

$$S_1^{piezo} = d_{31}E_3 \quad (2)$$

For practical PZT properties, Equation (2) that an inplane strain $S_1^{piezo} = 87.5 \mu\epsilon$ could be obtained with an electric field $E_3 = 0.5 \text{ kV/mm}$. For a typical PZT wafer of thickness $h = 200 \mu\text{m}$, this means a quite sizable applied voltage $V = hE_3 = 100 \text{ V}$. The associate power can be approximated as

$$P = \frac{1}{2} \omega C V^2 \quad (3)$$

where ω is the operating frequency and $C = N\epsilon_{33}A/h$ is the capacitance, with N the number of layer, $A = bl$ the electrode area, ϵ_{33} the electric permittivity of the piezo material. At, say, 100 kHz operation, Equation (3) yields $P_{200\mu\text{m}}^{1\text{-layer}} \approx 12 \text{ W}$. This situation, 100 V and ~12 W, reflects the state-of-the-art piezoceramic wafer technology (Figure 10a).

Replacing the 200- μm piezoceramic wafer with a 3- μm ferroelectric thick-film will decrease the voltage needed to achieve $S_1^{piezo} = 87.5 \mu\epsilon$ induced strain from 100 V to only 1.5 V (Figure 10b). The required power decreases from ~12 W to a mere ~0.180 W. However, the voltage value of 1.5 V is still too large for microwave-powered battery-less operation.

The voltage requirements can be further decreased and bring them within the microwave energized capabilities by adopting a multi-layer construction (Figure 10c); for $N = 100$ layers of 30 nm each, the above calculations yield a voltage of mere 0.015 V. This indicates that the thin-film nano-PWAS will decrease the required voltage by orders of magnitude less than current piezoceramic wafers (0.015 V vs. 100 V) and enable a microwave-powered battery-less wireless operation.

Figure 10 Proposed thin-film layered nano-PWAS would require orders of magnitude lower voltage (0.015 V vs. 100 V) to achieve the same inplane strain ($S_1 = 87.5 \mu\epsilon$)

4.3 Micro phased array of nano-PWAS transducers

The next step in complexity is to use the multi-layer nano-PWAS to create micro phased arrays. Priority claims^[11] and extensive experience with the use of PWAS phased arrays for efficient large-area damage detection from a single location. However, an inherent shortcoming and limitation of the phased array approach is the existence of a blind area in the array's near field. The blind area radius R is commensurable with the array aperture D , where $D \approx M\lambda/2$, where M is the number of elements in the array and λ is the wavelength of the particular Lamb wave mode excited in the structure ($\lambda = c/f$). Our previous studies on Lamb wave tuning with PWAS transducers have indicated that maximum excitation of a certain Lamb wave mode happens when the PWAS size a is in a certain relationship with the half wavelength $\lambda/2$. (More details of the PWAS Lamb-wave tuning principles are given in ref. ^{[13],[14]}) From these considerations, it is apparent that in order to reduce the blind area one has to construct PWAS transducers of smaller size a . E.g., a ten fold reduction in PWAS size a will ensure a ten fold reduction in the blind area D as well as a ten fold increase in the damage detection resolution $1/\lambda$. For these reasons, the development of nano-PWAS with small surface footprint (10 – 100 μm) is being pursued that will ensure a small phased array aperture and hence a small blind areas, as well as very good damage detection resolution.

Figure 11 Proposed nano-PWAS phased array showing quasi-annular interdigitated electrodes to ensure axisymmetric wave propagation from each transducer

A schematic of the proposed nano-PWAS phased array concept using annular IDT electrodes is presented in Figure 11. The annular IDT electrodes design was selected to ensure axisymmetric wave propagation from each transducer. (The electrodes planform was selected to be quasi-square in order to ensure an optimum coverage of the ferroelectric thin-film area; the corner effects in the wave field quickly even out, as revealed by numerical simulation). The IDT electrodes, which exploit the half-wavelength tuning with the selected Lamb-wave mode, will ensure that a quasi-radial electric field that is created and that this field alternates in sign between one electrode pair and the next. Through the half-wavelength relationship, this excitation pattern will ensure that the elastic ultrasonic Lamb waves emanate outward from the nano-PWAS center, and each nano-PWAS can be approximated with a point source in the idealized phased-array scheme. The IDT electrodes are reproduced identically at each after each ferroelectric thin-film layer.

4.4 Wireless battery-less operation via tag antennas

A major challenge in the SHM usability of the nano-PWAS device is to give it a non-battery wireless operational capability. The concept is to provide each nano-PWAS with a miniature tag antenna that can be remotely interrogated with microwave wireless power. The microwave beam pulse will energize the nano-PWAS into sending an interrogating Lamb wave/SAW pulse into the surrounding structure. The reflected/diffracted acoustic waves received back by the nano-PWAS will be transduced back into microwave field and emitted through the tag antenna. From an electromagnetic standpoint, this operation is similar to the well proven RFID technology. What is not yet fully understood is how to use the transduction between electromagnetic and acoustic domains to detect the incipient damage presence. Perceived research challenges include:

- (a) Separation of damage diffractions from those due to structural features and boundaries
- (b) Capability to detect weak acoustic wave signals and transduce them into electromagnetic waves of sufficient power to ensure adequate reception and interpretation
- (c) Development of new phased-array principles amenable to remote wireless interrogation

These fundamental challenges will be addressed using the previous work on damage detection with embedded PWAS arrays. Challenge (a), which is pervasive in the SHM research, will be addressed by developing a novel statistics-based differential imaging approach. Challenge (b) will be addressed by building on our previous work on efficient power and energy transfer through optimal interaction structural acoustic waves and PWAS transducers. Challenge (c) will be addressed by developing new principles of indexed-addressing of phased-array elements through wave modulation/encoding.

4.5 Experimental result and discussion

Analytical models for the electro-mechanical-acoustical analysis of the interaction between piezoelectric wafer active sensors (PWAS) and the guided-Lamb waves in the substrate structure^{[12],[13],[14]} have been developed. Analytical models of the bonding layer shear transfer and space-domain wavenumber. Fourier analysis of the guided Lamb waves predicted the possibility of preferential tuning of various Lamb-wave modes. These predictions have been experimentally confirmed. Tuned Lamb waves generated with PWAS arrays have been used to create guided-wave scanning beams to interrogate large structural areas^[11]. However, these arrays were much less effective when applied to small and compact structural parts of complicated geometry. Upon investigation, it was found that the tuned wavelength was insufficiently small to permit small area/incipient damage detection and that the blind area was relatively large. The thin-film approach of this project will provide a much smaller array for effective damage detection.

Figure 12 Multi-physics FEM simulation of the electric field lines during the piezoelectric poling process

Predictive modeling and experimental test are used to achieve the nano-PWAS developmental steps, from single-layer thin-film nano-PWAS up to the micro-phased array and the non-battery wireless operation. Careful analysis using advanced simulation and precise measurements is to be conducted. In brief, the main activities should consist of:

- 1) Modeling and experimental analysis of the piezoelectric interactions in the ferroelectric thin-film sensor applied to the structural substrate. This shows the use a multi-physics FEM code to analyze the poling process in a simple configuration explored in preliminary work. To achieve full understanding, one should use this approach to analyze the multitude of piezoelectric interactions and optimize the multi-layer configuration, ferroelectric thin-film/electrode thin-film ratio, antenna configuration, etc. In addition, one should develop reduced-order analytical methods to perform wider parameter search and optimization

- 2) Modeling and experimental analysis of the tuning between ferroelectric thin-film active sensor array and multi-mode dispersive Lamb waves in the structure. One should build on PWAS tuning expertise [13] to address the complicated problems appearing in multi-layer nano-PWAS working a MHz frequencies in micro phased arrays
- 3) Damage detection simulation and experimental validation with multi-layer nano-PWAS
- 4) Performance and durability testing of multi-layer nano-PWAS and development of guidelines and recommendations for quality improvement in collaboration with the other team members

5. CONCLUSIONS

In conclusion, thin-film active nano-PWAS were fabricated directly to the structural substrate using thin-film nano technologies. Nano-PWAS architectures consists of two parts, thin-film fabrication and nano-PWAS construction. The first part showed the thin-film successfully deposited on structure material . The ferroelectric BaTiO₃ (BTO) thin films were successfully deposited on structure material Ni and Ti by pulsed laser deposition under the optimal synthesis conditions. Microstructural studies revealed that the as-grown BTO thin films have the nanopillar structures and the good interface structures with no inter-diffusion or reaction. The dielectric and ferroelectric property measurements exhibit that the BTO films have a relatively large dielectric constant, a small dielectric loss, and an extremely large piezoelectric response with a symmetric hysteresis loop. Nano-PWAS construction and their relation to the active SHM interrogation methods were patented. The predictive modeling and experimental tests used to achieve the nano-PWAS development are discussed here. The research objective is to develop the fabrication and optimum design of thin-film nano-PWAS for structural health monitoring.

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