

Optimization of Phage-Based Magnetoelastic Biosensor Performance

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ABSTRACT

A magnetoelastic (ME) platform coated with a bio-molecular recognition element (bacteriophage) for selective and specific recognition of *Bacillus anthracis* spores is described. ME materials have a mass-sensitive, characteristic, resonance frequency. In response to the binding of spores to the phage on the ME biosensor, a corresponding decrease occurs in this resonance frequency, which enables the possibility of real time and *in-vivo* bio-detection. Experiments were performed to determine the annealing condition for the prevention of corrosion in aqueous environments. It was found that annealing at 200–250°C in a vacuum oven after gold deposition can effectively increase the ME platform's environmental stability, as well as the *Q*-factor and mass sensitivity of the ME biosensor. Another set of variables involves the concentration of phage suspension as well as the concentration of salts contained in phage solution. Based on the sensor response and SEM results, a phage concentration of 1×10^{11} vir/ml and a salt concentration of 420 mM in 1x TBS provide the best sensor performance in terms of binding sensitivity.

Keywords: magnetoelastic, biosensor, phage, annealing, bundling, *Bacillus anthracis* spores

1 INTRODCTION

Fears of deliberate contamination of our food supply and the threat of terrorist attacks using *Bacillus anthracis* have created increasing concerns. Traditional methods of detection such as PCR [1] and antibody-based ELISA techniques [2] can be complicated and exhibit poor specificity in harsh environments. New detection methodologies are needed to address the threat of bioterrorism. Recently, filamentous phage fd has been successfully shown to be an alternative to antibodies as a robust bio-molecular recognition element for biosensors [3]. The combination of phage with magnetoelastic (ME) sensor platforms provides a simple, specific, and wireless detection method. The sensor platforms were prepared from ribbons of Metglas® alloy 2826MB. The genetically engineered phage for binding *B. anthracis* spores was produced by Dr. Petrenko [4] of Auburn University's College of Veterinary Medicine. Biosensors are formed by immobilizing phage directly onto the surface of the ME platforms.

As ME-based biosensors are relatively new, the objective of this paper was to investigate several variables to optimize the performance of ME biosensors for the

detection of *B. anthracis* spores. Since ME materials are iron-based, a gold surface layer is required for corrosion resistance, as well as biocompatibility (phage immobilization). Also, since these sensor platforms are deposited by sputtering, they must be annealed prior to use in order to reduce the effect of as-sputtered defects. Experiments were performed to determine the annealing condition for the prevention of corrosion in aqueous environments. Another set of variables involves the ideal conditions for the immobilization of the phage onto the gold surfaces of the sensor platforms. Filamentous phage tends to form bundles due to polarization-based, attractive interactions. Bundling leads to a reduction in exposed protein binding sites and reduces the overall binding affinity of the biosensor surface. Key parameters that influence bundling are the concentration of phage in the solution, as well as the chemistry of the phage solution, specifically salt concentration.

2 MATERIALS AND METHODS

2.1 Biosensor Platform

ME sensors were made from the ME strips (Metglas alloy 2826MB, Fe₄₅Ni₄₅Mo₇B₃, Honeywell) and hand-polished to 15µm thickness. A micro-dicing saw was then used to cut the alloy into the size of 2 x 0.4 mm. These platforms were rinsed with fresh acetone, methanol, and finally dried in air to remove the adhesives used in the dicing process.

2.2 Pre-coating and Annealing

As mentioned before, the ME materials are principally Fe and easily corroded. In addition, the buffer (i.e. TBS) and bacteria solutions used for the experiments contain a certain amount of salt, which will accelerate corrosion. So, after annealing, some pre-coating is necessary to protect the ME platform. Two layers of thin films (Cr & Au) were sputtered onto both sides of the sensor platforms by using a magnetron sputtering system (Denton Vacuum Discovery-18) with two cathodes (RF and DC). The Cr layer was deposited first which in order to improve the adhesion between the ME platform and the Au layer. Additionally, it provides extra electrochemical resistance from corrosion. The Au layer was then deposited not only to protect the ME material from degradation in the saline solutions, but also to provide a bioactive surface upon which the biological agents (bacteriophage here) may be easily adsorbed. The whole deposition process is accomplished by a Denton™ Vacuum Discovery-18 sputtering system (Moorestown, NJ) without breaking the vacuum. Table 1 lists the sputtering conditions.

Table 1 Sputtering conditions for ME sensor pre-coating

	DC	RF
	Cr	Au
Pre-sputter Power (w)	100	100
Pre-sputter Time (s)	300	300
Sputter Power (w)	100	100
Sputter Time (s)	300	600
Sputtering rate (nm/s)	0.308	0.231
Pressure (mTorr)	5-6	
Sputter Gas	Ar	
Vacuum (Torr)	5x10 ⁻⁶	

In order to remove the residual stress as well as the as-sputtered defects, an annealing process was employed. This was carried out at 70°C, 150°C, 200°C, 250°C or 300°C for 2 hours in a vacuum oven, under a vacuum of at least 10⁻³ Torr. Afterwards, the samples were cooled to room temperature in the oven while still under vacuum.

2.2 Bacteriophage Immobilization and Spore Binding Measurements

The filamentous phage clones JRB7 with a concentration of 1.06×10¹² vir/ml were kindly provided by Dr. Barbaree of Department of Biological Sciences at Auburn University. In order to prepare phage solution containing different amounts of NaCl, dry NaCl was added to 1xTBS (25mM Tris, 3mM KCl, and 140mM NaCl at a pH of 7.4) solution separately to obtain five different salt concentrations: 140mM, 280mM, 420mM, 560mM, and 840mM. Then, JRB7 phage solution was diluted by the series of 1xTBS solutions above to obtain phage concentration of 1.06×10¹¹ vir/ml in five different concentrations of NaCl. This set of conditions was chosen to investigate the effect of the phage/salt ratio on the distribution of phage immobilized on the sensor, which in turn effects the binding affinities of the ME biosensors. Each NaCl condition was repeated for 5 individual sensors.

Phage was immobilized on the sensor surface by incubating the ME particles in the phage solutions (300μl). Following this step, the sensors were rinsed with distilled water three times to remove any loosely bound phage and any salts remaining from the buffer solution, and then transferred to clean PCR tubes. Spore solutions were then added into these tubes and allowed to incubate for another 1 hour, followed by another distilled water rinse.

2.3 Operation Principle and Analyte Binding Measurement

ME materials, when exposed to a time-varying external magnetic field, can be resonated due to the change in their dimensions. For a thin (i.e. length is much larger than the thickness), ribbon-shaped sensor of length L , vibration will be mainly along the length direction at its fundamental resonant frequency. This frequency is given as equation (1) [5]:

$$f = \frac{1}{2L} \sqrt{\frac{E}{\rho(1-\nu^2)}} \quad (1)$$

where E , ρ and ν are the Young's modulus of elasticity, density, and the Poisson's ratio of the sensor material, respectively. The resonance frequency is dependent on geometry as well as mass. With an additional mass load on the sensor surface, a shift in the resonance frequency (Δf) will result as described by equation (2) [6]:

$$\Delta f = -\frac{f}{2} \frac{\Delta m}{M} \quad (2)$$

where f is the fundamental resonance frequency, Δm is the mass change on the ME material, and M is the initial mass of the ME material. Fig.1 illustrates the wireless nature of the individual sensor and the basic principle for detecting bound mass (spores) in air. In our research, after phage immobilization the characteristic resonance frequency for each sensor was measured as f_0 . And after exposure to the spore solution, the frequency was measured as f_{mass} . As spores are captured by the specific phage on the sensor's surface, the mass added onto the sensor increases, resulting in a frequency shift to a lower value.

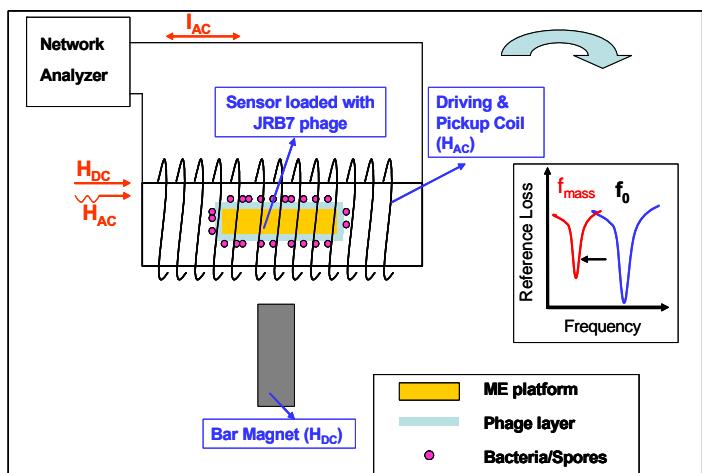


Fig.1 Setup for ME biosensors measurement

2.4 Microscopic Analysis

A JEOL-7000F scanning electron microscope (SEM) was used to confirm and quantify the binding of target antigens to the phage-coated ME biosensors. In order to count the number of spores bound to the sensor's surface, the entire surface of one side of the sensor was photographed and the spores were counted individually. This number was then multiplied by 2 to account for the total number of spores on both sides of the sensor. In preparation for SEM observations, the biosensors were washed with distilled water and then exposed to osmium tetroxide (OsO₄) vapor for 40 min, followed by coating with 60 nm thickness of Au to provide a conductive surface for SEM imaging. A PHILIPS-301 transmission electron microscope (TEM) was used to verify the interaction of bacteria and spores

with the corresponding phage. The TEM samples were prepared on 400 mesh formvar/carbon coated nickel grids. The grid was floated on a drop of sample solution for one hour. Upon removal from the drop, excess fluid was drained from the grid by touching its edge to filter paper. Then the grid was washed gently with one drop of stain solution (PTA) and floated on another drop of stain solution for 3 min to obtain a negative stain of the sample. The grid was allowed to dry before examination.

3 RESULTS AND DISCUSSION

3.1 Effect of Annealing

Fig.2 (1) shows the SEM picture of a sensor without annealing. As can be seen, the micro-cracks are the main characteristic of the surface morphology. We hypothesized this was due to internal residual stress generated during the original material manufacture and/or from the polishing/dicing operations. In order to show the effect of annealing, six groups of sensors were annealed under six different temperatures, with the resonance frequency of each sensor being measured and compared before and after annealing. The spectrum quality (Q) factor and the amplitude of frequency signal are the main elements to represent the performance of the sensors. The Q -factor is given by:

$$Q = \frac{f_0}{\Delta w} \quad (3)$$

where f_0 is the resonance frequency and Δw is defined as the peak width where the amplitude falls to half of its maximum value. Fig.2 (2) shows the trends of Q -factor and amplitude change after annealing under different temperatures as well as the surface microstructure change under those conditions. As temperature increases from 150°C to 300°C, the Q -factor of the sensors can be observed to increase until a maximum is achieved between 200°C and 250°C. As temperature is increased further to 300°C, the Q -factor of the sensors decreases by about 60%. Since a higher Q -value means a more accurate determination of the resonance frequency, the optimum annealing temperature is in the range of 200°C-250°C. A similar trend for amplitude was found as well. It is clear to see that the amplitude reached a maximum after annealing at 200°C. This phenomenon can be explained by SEM images. Compared with the picture (Fig.2 (1)) of no annealing, there are still some of the cracks on the surface after annealing at 150°C. When annealed at 200°C, the surface became much smoother, and the cracks disappeared when the temperature was about 250°C. However, the cracks started to show up again when the annealing temperature was increased to 300°C. Within the optimum annealing temperature range of 200-250°C, the residual stresses are removed and the structural defects are also corrected.

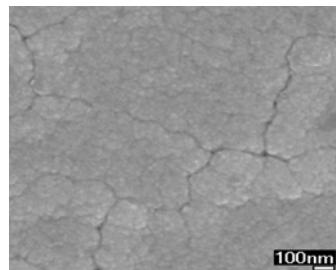
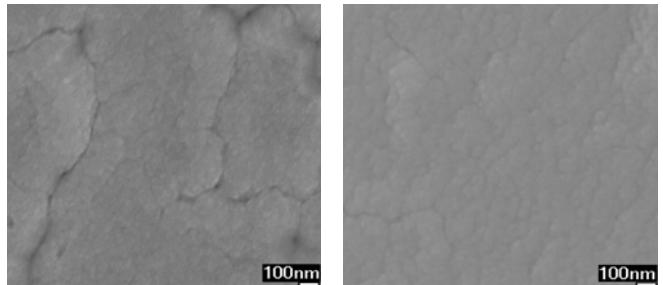
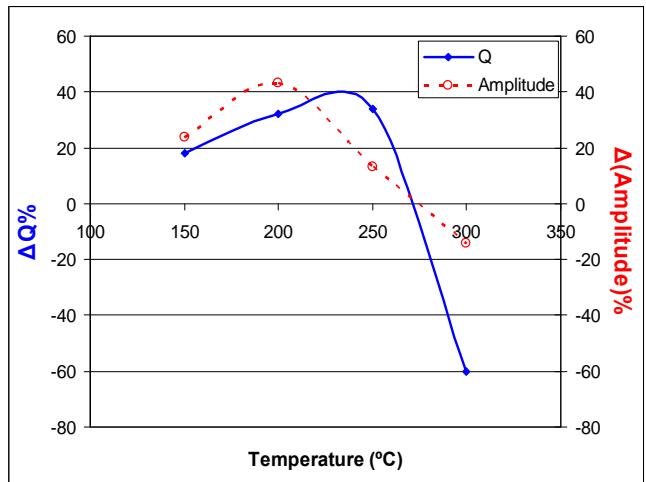
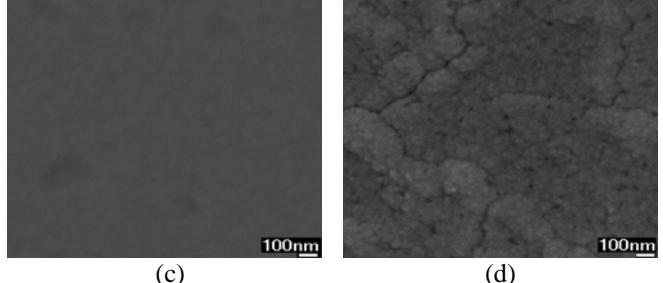


Fig.2 (1) SEM images of sensor surface before annealing



(a)

(b)



(c)

(d)

Fig.2(2) The effect of annealing temperature on Q factor and amplitude of the resonance frequency and SEM images of sensor surface after annealing under different temperatures: (a) 150°C; (b) 200°C; (c) 250°C; (d) 300°C.

3.2 Effect of Salt Concentrations

Fig.3 shows the TEM pictures of phage distribution at different salt concentrations. The phage filaments tend to

cluster together when the solution contains 140mM NaCl. This is the phenomenon called “phage bundles”. As the amount of NaCl is increased to 420mM, the resolubilization of bundles is observed. Upon increasing to 840mM NaCl, the bundles formed again. There are four negative charges for each protein coat of a single phage (Wen and Tang, 2006). When the phage solution contains a small amount of counterions (Na^+), the phage filaments will start to neutralize, which leads to bundling. As the amount of Na^+ ions is increased, disaggregation of the filaments occurs. When the Na^+ concentration becomes too high, there will be not enough water molecules to hydrate all the counterions, which results in formation of bundles again [8].

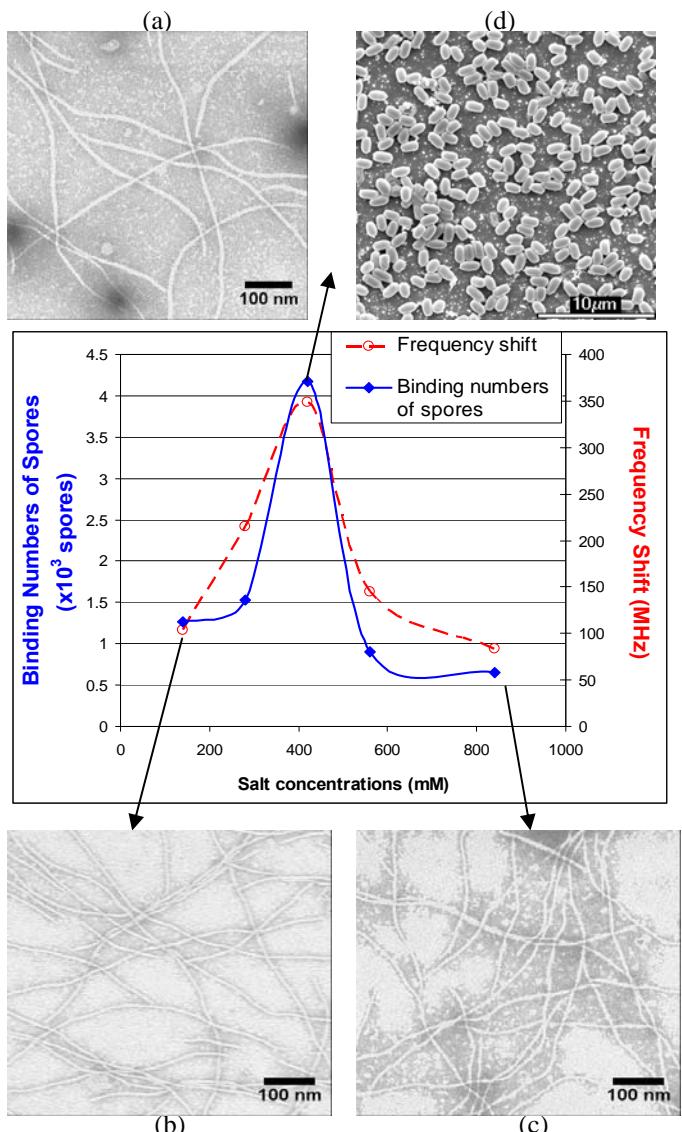


Fig.3 Frequency shift and spore binding numbers of sensors at different salt concentrations in 10^{11} vir/ml phage solution. TEM photographs of phage in selected NaCl concentrations: (a) 140mM, (b) 420mM, (c) 840mM. SEM photographs (d) of spore binding of sensor immobilized with 10^{11} vir/ml phage in 420mM NaCl solution.

The frequency shift results as well as the binding numbers of the spores counted based on the SEM pictures is summarized in Fig.3. Both of them show very similar trends. When the salt concentration is increased from 140mM to 840mM, the frequency shift and spore binding numbers increases until a maximum is achieved at a salt concentration of 420mM. As NaCl concentration is increased further, the shift in resonance frequency and the number of bound spores decreases. As seen in Fig.3 (b), the binding is uniformly distributed. This is consistent with the results obtained from the TEM observations. When phage bundles, it leads to a reduction in exposed protein binding sites and reduces the overall binding affinity of the biosensor surface. The result of this is that a lower number of spores will be able to bind onto the sensor. Since a higher amount of binding on the sensor corresponds to a higher frequency shift of the biosensor (as per Eq.2). It is evident that the 420mM salt concentration represents the optimum binding condition for 10^{11} vir/ml phage solution.

4 CONCLUSIONS

The optimization of phage based ME biosensors performance by using annealing and modifying the chemistry of filamentous phage solution has been established. By annealing between 200-250°C in vacuum oven after sputtering, the residual stress created during dicing is largely relieved and many of the structural defects will be removed. Afterwards, the *Q*-factor of the resonance signal increased by about 30% and the amplitude increased by about 25%. By increasing the amount of NaCl in the 5×10^{11} vir/ml phage solution to 420mM, the tendency of the phage filaments to bundle will be minimized, thereby increasing the available binding sites on the ME sensor’s surface. The result is that more spores will be able to be bound to the sensor surface, increasing the binding affinity of the ME biosensor.

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