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Color changing block copolymer films for chemical sensing of simple sugars

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ABSTRACT

We investigated the use of functionalized photonic block copolymer films for the detection of glucose. Polystyrene-b-poly(2-vinyl pyridine) (PS-b-P2VP) block copolymers were chemically functionalized with 2-(bromomethyl)phenylboronic acid and cast into films that reflect a visible color when exposed to aqueous media. The 2-(bromomethyl)phenylboronic acid functionality can reversibly bind to glucose. When exposed to high concentrations of glucose the polymer responded with a red shift in color. Low concentration exposure of glucose caused the polymer films to blue shift in color. The BCP films also exhibited a selective response to fructose, mannose or galactose, giving a different response depending on which sugar is present. The color of the polymer was tuned to blue, green, yellow or orange by varying the film's crosslink density. The color change can be visually observed without the use of equipment such as a spectrometer.

1. Introduction

Chemical sensors have been developed from a wide array of materials that can change color upon exposure to a target molecule. These sensor systems are generally based on photonic crystals that have been modified to recognize the target molecule. The photonic crystal contains periodic nanostructures with differing indices of refraction that interact with visible light. The material can be functionalized to recognize or bind to specific chemical targets. Recognition of the target will alter the spacing of the periodic nanostructure thereby changing the way it interacts with visible light. The advantage of such systems lies in producing a discernable change in color. This concept has been applied in the fabrication of colloidal hydrogel systems, porous silicon systems as well as through the use of lithography techniques on other substrates. Asher et al. demonstrated the use of a photonic crystal polymerized colloidal hydrogel system (Cui et al., 2009; Lee and Asher, 2000). Such material could act as a sensor for glucose but required the complex process of synthesizing monodisperse, highly charged polystyrene particles. Porous silicon (Lee and Fauchet, 2007; Li et al., 2003) and nanoprint lithography (Endo et al., 2010) have also been reported as photonic crystal chemical sensing platforms. These systems can be problematic in producing a discernable response without analytical measurements. Therefore, a sensor that can be easily fabricated and yield an instantaneous, visibly discernable response is needed.

One of the material systems investigated for its use as photonic crystals is self-assembled microphase separated layers in block copolymer films (Edrington et al., 2001; Kang et al., 2007; Urbas et al., 2000). Block copolymers (BCPs) consist of two or more chemically distinct sequences of monomer repeat units linked together through a covalent bond. Upon evaporation from a solvent, BCPs will microphase separate into solid films displaying a number of different morphologies (e.g. hexagonal, cubic, gyroid, lamellar) depending on the relative volume fraction of each block (Bates and Fredrickson, 1990). BCPs in which both blocks are of equal molecular weight generally exhibit the lamellar morphology. Self-assembly into a lamellar morphology is significant in producing a BCP photonic crystal. If there is enough contrast in refractive index between the two blocks in the lamellar structure then certain wavelengths of light will be reflected by the material. This phenomenon is dictated by:

$$\lambda_1 = 2(n_1 d_1 + n_2 d_2)$$

where λ_1 is the reflected wavelength, n_i is the refractive index of layer i and d_i is the thickness of layer i[6].

In this study, the diblock copolymer polystyrene-b-poly(2-vinylpyridine) (PS-b-P2VP), which microphase separates into a lamellar periodic stack, was explored for its use as a chemical sensor to detect and respond to glucose with a change in color. The 2-vinyl pyridine (P2VP) block was quaternized

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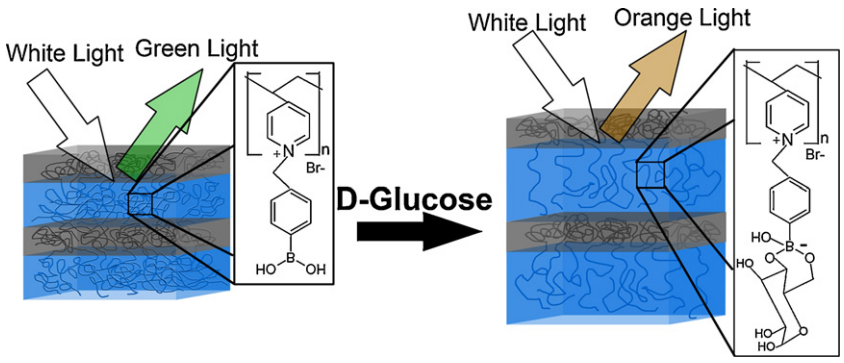

Scheme 1. Schematic depicting the BCP film color change. Initially the BCP film is in deionized water. The positive charge on the pyridine allows the P2VP block to swell in the water. This gives the BCP film sufficient thickness to reflect visible light, in this case green light. When D-glucose is introduced it binds to the phenylboronic acid functionality which lowers the pKa of the boronic acid forming the negatively charged boronate complex. The additional negative charge swells the BCP film causing it to reflect light in the wavelength of orange.

with 2-(bromomethyl)phenylboronic acid, which placed a positive charge on the pyridine ring of the block. This charge allows the BCP film to swell in aqueous media. The swelling changes the thickness of the block allowing it to interact with wavelengths of visible light. Kang et al. (2007) have reported lamellar PS-b-P2VP films quaternized with bromoethane, which places a positive charge in the P2VP block, and attaches an ethyl group to the nitrogen atom. In our work, the quaternizing agent used contributes a boronic acid residue, giving the BCP the ability to bind to sugars such as glucose. We hypothesized that binding would induce a change in the distance between the lamellae causing a change in the wavelength light reflected by the polymer, thus allowing the BCP to act as a glucose sensor.

Boronic acids have been of great interest in chemical sensing due to their ability to covalently bind to sugar molecules such as glucose (Bosch et al., 2004; Chen et al., 2009; Kim et al., 2007). Although sensing glucose has applications in diabetic medicine our decision to explore glucose sensing using the boronic acid functionalized BCP system, was designed to serve as a model system to test the concept that block copolymer based photonic crystals can be fabricated to act as chemical sensors for small molecule detection. In the work described in this manuscript, the polymer film was tested for successful attachment of the boronic acid, retention of the lamellar morphology post-functionalization, and sensitivity and specificity to simple sugar binding.

A schematic of the BCP film sensor can be seen in Scheme 1. Initially the BCP film is fabricated to exhibit a periodic lamellar stack. The P2VP block of the block copolymer is functionalized with phenylboronic acid placing a positive charge on the pyridine ring, which allows the P2VP block to swell in aqueous media until its thickness is large enough to interact with visible light, in this case reflecting green light. The phenylboronic acid can bind sugars and will do so when exposed to a glucose solution. As shown in Scheme 1 the boronic acid binds to the 1,3 diol functionality. It has been reported that this is the kinetically favored binding site on glucose as well as the 1,2 cis diol (Bielecki et al., 1999). This binding event lowers the pKa of the phenylboronic acid causing it to form the negatively charged boronate complex. The negative charge triggers additional swelling of the BCP film changing it color from green to orange. We have shown that after functionalization the BCP film can respond to a glucose solution and shows a selective response when exposed to different sugars such as fructose, mannose or galactose.

2. Methods

2.1. Fabrication of photonic BCP films

The procedure for fabrication of the PS-b-P2VP films was adapted from Kang et al. (2007). The PS-b-P2VP block copolymers were purchased from Polymer Source (Montreal, Canada). The molecular weight of each block of the copolymer was 133,000 g/mol. A 5% weight/volume stock solution of PS-b-P2VP was prepared in propylene glycol monomethyl ether acetate (PGMEA). The films were prepared by spin-casting 300 μl of the PS-b-P2VP solution onto 1″ × 1″ glass slides at 350 rpm for 2 min. The glass slides were purchased from Ted Pella (Redding, CA), and were functionalized with 3-(aminopropyl)triethoxysilane. The spin-cast block copolymer films were subsequently annealed in chloroform vapor at room temperature for 24 h to allow them to self-assemble into a lamellar structure.

2.2. Functionalization and tuning of photonic properties

The P2VP block of the spincast films was quaternized with 2-(bromomethyl)phenylboronic acid. The quaternization reaction places a phenylboronic acid functional group in the P2VP block, allowing the polymer to bind sugars such as glucose. The quaternization reaction was carried out by immersing the spincast, annealed block copolymer films in a solution of 40 mg of 2-(bromomethyl)phenylboronic acid in 40 ml of acetonitrile and allowing it to reflux for 5 h. The quaternized polymers were then removed from the solution and dried in a 50 °C oven for 1 h. To tune the optical properties of BCP film a crosslinking agent, 1,4-dibromo-2-butanol, was introduced into the acetonitrile solution. Different molar ratios of 2-(bromomethyl)phenylboronic acid to 1,4-dibromo-2-butanol were tested at 0.05 mmol as the total monomer amount. The same protocol was used to investigate the effect of different degrees of crosslinking on the color of the BCP films.

2.3. Characterization

Fourier transform infrared spectroscopy (FTIR) was utilized to determine whether the boronic acid functionality was successfully attached. The functionalized polymer film was removed from the glass slide by immersion in a 5%v/v aqueous solution of hydrofluoric acid. The freestanding polymer film was dried for 24 h in a 50 °C oven. An FTIR spectrum was obtained of the functionalized polymer film using a Thermo Nicolet FT-Raman, Model 670. To determine