CdTe quantum dots film by electrospinning as bearing temperature sensor

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Abstract. Temperature monitoring of bearing rotating elements is crucial for bearing condition assessment and early warning. Using CdTe quantum dots (QDs) to prepare sensors requires other membrane material as the substrate, which affects the accuracy of the test. Meanwhile, CdTe QDs exposed to air for long time will lead to oxidation, which affects the storage life of the sensors. Hence, based on excellent film forming properties of polyvinyl alcohol (PVA), the CdTe/PVA polymeric nanofiber was fabricated by electrospinning method. For comparison, the CdTe/PVA composite film by drop-casting method was also prepared. Thermal properties show that there are excellent linear relationships between peak wavelength and temperature of the CdTe/PVA composite film and the CdTe/PVA polymeric nanofiber respectively. However, the uniformity of the CdTe/PVA polymeric nanofiber obviously better than the CdTe/PVA composite film. Outstanding temperature dependence of photoluminescence spectra and uniform film formation demonstrating the potential value of the obtained CdTe/PVA polymeric nanofiber as temperature sensor for bearing rotating elements.

1. Introduction
As basic mechanical components, rolling bearings are widely used in machinery. With the increasing of rotation speed and load, rolling bearings face more complex and harsh service environment. It is of great significance to carry out on-line monitoring of high-speed rolling bearing performance for the health assessment and early warning of mechanical equipment. Temperature is one of the most important performance index to evaluate the service state of high-speed bearing. The work by Kovacs et al. [1] indicates that temperature of bearing rotating elements (inner ring/cage) is more sensitive to its service state. At present, the main temperature monitoring methods of bearing rotating elements including infrared thermometer and wireless temperature sensor [2]-[4]. These methods have some problems, such as disturbed by environment easily and low test speed, which limited their application. Based on the temperature dependence of CdTe quantum dot (QDs) photoluminescence (PL) spectra, our research team proposed a novel temperature monitoring method of bearing rotating elements [5], [6]. By this method, the temperature of bearing inner ring and cage can be obtained successfully without changing bearing structure and affecting bearing motion. More importantly, this method is not limited by bearing speed in theory, and it has been successfully used in bearing temperature monitoring at 15000 r/min. However, the preparation of CdTe QDs sensor for bearing temperature measurement needs polydimethylsiloxane (PDMS) film as the substrate, so that the bearing has not direct contact with the CdTe QDs, which affects the accuracy of the test. Simultaneously, the CdTe QDs directly exposed to the air for long time may lead to oxidation, which has a great impact on the
storage life. Therefore, the research of QDs film-forming technology is the key of bearing temperature monitoring.

In practical applications, QDs are usually dispersed in inorganic or organic polymers, which can improve their stability and facilitate the processing of QDs devices. Therefore, the efficient preparation method of QDs/polymer composites provides the idea for CdTe QDs film formation. Recent years, polyvinyl alcohol (PVA) is widely used as polymer matrix due to it has good chemical and thermal stability, excellent film-forming properties and good transparency. However, there are still many problems when QDs are directly dispersed in polymers, such as the increase of surface defects, poor dispersion and easy agglomeration, which lead to the instability of fluorescence intensity and the decrease of quantum efficiency [7]. Electrosprining technology has attracted extensive attention in the fields of physics, chemistry and biomedicine due to its simple method, environmental friendliness, low cost and high efficiency [8]. Loading QDs with excellent photoelectric properties into polymer nanofibers by electrosprining technology not only endows the nanofibers with special optical properties, but also improves the stability and fluorescence properties of QDs.

In this work, the CdTe/PVA polymeric nanofiber was fabricated by electrospinning method. For comparison, the CdTe/PVA composite film by drop-casting method was also prepared. An experiment system of temperature calibration was built to evaluate the thermal properties of the as-fabricated QDs sensors by tracing the PL spectra with temperature. The results show that there are excellent linear relationships between peak wavelength and temperature of the CdTe/PVA composite film and the CdTe/PVA polymeric nanofiber respectively. By comparison, the uniformity of the CdTe/PVA polymeric nanofiber is obviously better than the CdTe/PVA composite film. Therefore, the as-fabricated CdTe/PVA polymeric nanofiber demonstrating the value as the temperature sensor for bearing rotating elements.

2. Experimental Section

2.1. Synthesis of CdTe/PVA solution
The synthesis of CdTe QDs solution follows the procedure given by our previously reported paper [4]. The PVA (1 g) was dissolved in deionized water (10 ml) in a sealed 25 mL round-bottom flask. The reaction was kept under vigorous stirring (1000 rpm) at 85 °C for 2 h to dissolve the PVA completely. After the PVA solution slowly cooling down to room temperature, the pre-synthesized CdTe (2 mL) was added to the PVA solution during stirring (1000 rpm) at 25 °C for 4h. Following that, the CdTe/PVA solution was obtained.

2.2. Preparation of CdTe film and CdTe/PVA composite film
The CdTe QDs solution was applied to the PDMS film (50 μm) by drop-casting method and dried in a vacuum drying oven for 2 h. Then the CdTe film attached to PDMS film was obtained. Similarly, the CdTe/PVA solution was applied to the PDMS film by drop-casting method and dried in a vacuum drying oven for 2 h. Then the CdTe/PVA film can be separated from the PDMS film, and the CdTe/PVA composite film was obtained. One particular concern is that the size of the film by drop-casting method can be controlled on the demand.

2.3. Preparation of CdTe/PVA polymeric nanofiber
The electrospinning apparatus was shown in Fig.1. The CdTe/PVA solution was inhaled into a dry syringe, and the syringe was fixed in the micro injection pump slot. The distance between the syringe needle and the receiving device was set as 10 cm, and the injection speed of the syringe was set as 0.2 nm/min. Then, the high voltage (16 kV) was applied to the special syringe needle. Electrospinning was carried out at the temperature of 30 °C and air relative humidity of 30%. Along with the solvent evaporates, the CdTe/PVA polymeric nanofiber can be collected on the receiver. Finally, the CdTe/PVA polymeric nanofiber was dried in a vacuum drying oven to remove the residual solvent.
2.4. Calibration system of temperature sensor
An experiment system of temperature calibration was used to evaluate the thermal properties of the as-fabricated QDs sensors by tracing the changes in the PL spectra with temperature. The calibration system mainly contains laser, spectrometer, optical fiber, electric heating plate, platinum resistance temperature sensor, MX data acquisition system and computer (Fig. 2). The laser and spectrometer are used to excite and collect the PL spectra of QDs sensor, respectively. The optical fiber is used for optical transmission. The electric heating plate is used to control the QDs sensor at different temperatures. Three platinum resistance temperature sensors and MX data acquisition system are used to monitor the actual temperature of the QDs sensor. The average temperature acquired by the three platinum resistance temperature sensors which around the QDs sensor closely on the heating plate is regard as the temperature of the QDs sensor. The computer is use to display the experimental data.

3. Results & Discussion
The CdTe/PVA polymeric nanofiber were fabricated by electrospinning method. For comparison, the CdTe film and CdTe/PVA composite film were also prepared. Fig.3 shows the CdTe QDs solution, CdTe film, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber under ambient light and UV irradiation (325 nm excitation) respectively. It can be seen that all films have high fluorescence, which is beneficial to the monitoring of PL spectra in practical engineering application. Moreover, the size of all three films can be small enough to suit the narrow space structure of bearing rotating elements.
Fig. 3. Digital photos of CdTe solution (a), CdTe film (b), CdTe/PVA composite film (c) and CdTe/PVA polymeric nanofiber (d) under ambient light and UV irradiation (325 nm excitation), respectively.

3.1. Thermal properties

The thermal properties of CdTe film, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber were evaluated via the temperature sensor calibration system as described in the Experimental Section. As shown in Fig. 4, the PL spectra of the CdTe film, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber were recorded respectively as temperature was increased from room temperature (about 20 °C) to 80 °C. It can be seen that the peak wavelength of the spectra of CdTe film, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber all exhibit distinctly red shift with the increase of temperature.

Fig. 4. The PL spectra of CdTe film (a), CdTe/PVA composite film (b) and CdTe/PVA polymeric nanofiber (c) with the temperature increasing.

The temperature dependence of peak wavelength of PL spectra of CdTe film, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber are exhibited in Fig. 5 (a)-(c) respectively. The linear relationship parameters of CdTe film, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber are summarized in Table 1. Adj.R-Square is the goodness of fit, which represents the degree of linear fit. In linear fitting, the closer its value is to 1, the better the linearity is. As shown in Fig. 5, all films have obviously linear relationship between temperature and peak wavelength of their PL spectra respectively, which can be confirmed from Table 1 that their Adj.R-Square’s value all exceeding 0.995. The slope of linear fitting represents the change of peak wavelength with temperature rise 1 °C. The larger the slope is, the greater the change of peak wavelength caused by temperature change is. Large slope is beneficial to the monitoring of spectral changes. It can be seen from Table 1 that the slope of linear fitting of CdTe/PVA composite film and CdTe/PVA polymeric nanofiber are obviously improved than CdTe film. Moreover, the slope of linear fitting of CdTe/PVA
The superior film-forming ability and linear relationship of CdTe/PVA composite film and CdTe/PVA polymeric nanofiber make both of them excellent candidates for use as temperature sensor. Poor uniformity of sensor may lead to data fluctuation, which will cause monitoring error when monitoring the temperature of bearing, especially for cage because of the large vibration during bearing operation. In order to analyze the uniformity of CdTe/PVA composite film and CdTe/PVA polymeric nanofiber, fifteen positions were randomly selected on the surface of CdTe/PVA composite film and CdTe/PVA polymeric nanofiber respectively. Then the change of peak wavelength of CdTe/PVA composite film and CdTe/PVA polymeric nanofiber at room temperature with different position were measured respectively. As shown in Fig.6, the peak wavelength of CdTe/PVA composite film at different positions have obvious fluctuation between 568.862 and 572.946 nm. By comparison, the peak wavelength of CdTe/PVA polymeric nanofiber at different positions have slight fluctuation between 561.712 nm and 562.46 nm. Meanwhile, it can be also seen in Fig.3 that the uniformity of CdTe/PVA polymeric nanofiber is better than CdTe/PVA composite film, which is consistent with the uniformity experiment.
4. Conclusions
Focusing on the problem of CdTe QDs film formation, this work has successfully demonstrated a simple strategy to synthesize CdTe/PVA polymeric nanofiber by electrospinning. By introducing CdTe QDs into PVA, CdTe/PVA composite film and CdTe/PVA polymeric nanofiber were prepared by two different processes. The thermal properties show that there are excellent linear relationships between peak wavelength and temperature of CdTe/PVA composite film and CdTe/PVA polymeric nanofiber respectively. Comparing with CdTe/PVA composite film, the uniformity of CdTe/PVA polymeric nanofiber obviously better. The obtained CdTe/PVA polymeric nanofiber can serve as temperature sensor for bearing rotating elements.

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