MEMS TEMPERATURE CHARACTERIZATION BY CdSe QUANTUM DOTS

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Abstract: Non-contact temperature measurements of MEMS structures using CdSe quantum dots (QDs) have been successfully demonstrated for a 1mm-long, 40μm-wide aluminum micro heater. Single quantum dot wavelength shift with respect to temperature was first characterized in the 25~65°C as 0.24nm/°C. Temperature profiles under different input power are evaluated based on the spectrum shift of bulk quantum dots on the heater and compared with a one-dimensional electrothermal model. Both experiments and simulations are consistent with variations of less than 0.8°C over the entire length of the heater. The theoretical spatial resolution of this technique can go down to the size of a quantum dot for non-contact temperature characterizations of micro/nano structures, including biological samples.

Keywords: CdSe quantum dots, temperature characterization, MEMS heater.

Introduction

When the characteristic dimension of active functional structures goes down to nanometer range, conventional temperature measurement techniques encounter challenges in both contact and non-contact schemes due to spatial resolution [1,2]. Quantum dots, with nominal sizes in the nm range and their favorable photostability [3], could potentially be used as novel temperature markers for micro/nano structures. Previous works [4,5] have reported that the emission spectrum of CdSe QDs bulk sample shifts with temperature. This work presents the emission spectral shift of a single QD in the 25~65°C range and its usages for the non-contact temperature characterizations. Possible applications to thermal metrology of micro/nano structures, chemical reactions and biological cells are a few of MEMS/NEMS uses; we present results obtained with MEMS heaters.

Figure 1 shows schematically, how CdSe QDs with a nominal size of 15~20nm in diameter can be used to detect temperature changes in a non-contact manner. A 532-nm green light laser is used to excite the QDs on micro/nano devices or inside biological samples through a microscope (Olympus, IX71) and the emission light from QDs is collected through a dichroic mirror (560lp, Chroma) to reject the excitation light, dispersed by a monochromator (Acton-Research, SP2150i, grating 1200 g/mm blazed at 500nm) and finally recorded by a intensified Cascade Camera (512B, Roper Scientific). When local temperature changes, the emission spectrum of QDs shifts and reveals each QD's local temperature.

Fig. 1. *The schematic diagram of non-contact temperature characterization using quantum dots by detecting their emission spectrum shifts.*

Temperature Calibration

CdSe quantum dots are encapsulated by ZnS shell and coated with polymer and conjugated with streptavidin (Qdots, invitrogen) and their nominal emission wavelength is 655nm. Experimentally, QDs solution was diluted in PBS (Phosphate–Buffered Saline) to 0.5pM and 20ul of this dilution was sandwiched between two 24

×50mm^2 glass cover-slips. After a period of 10-minute incubation at 100°C, the cover-slips were separated and 10ul of PDMS (1:1 mixture of base and curing agent) was added on one cover-slip to fix the position of quantum dots. Afterwards, a 22×22mm^2 glass cover-slip was covered on the sample and sealed by nail polish on the edges.

Total Internal Fluorescence Reflection Microscopy (TIRFM) has been used in calibration to acquire the image and spectrum of individual quantum dot. The TIRF objective is 100× with N.A. 1.40. A thermocouple (5SC-TT-K-36-36, Omega Engineering, Inc.) was taped onto the top of small glass cover-slip beside the observation point to monitor the local temperature.

The concentration of the quantum dots sample is low to differentiate each single quantum dot as shown in figure 2(a), where about 10 single QDs are recorded in an area of 80×10μm^2. A slit in the monochromator was utilized to get rid of the influence of other QDs outside the center line region in the image. Then the wavelength of monochromator was set to 655nm to disperse the spectrum of each single quantum dot inside the image scope into vertical lines as shown in figure 2(b). Because of the fluorescence intermittency, not all the quantum dots in Fig. 2(a) show their spectra in Fig. 2(b). The center of the image in the y axis indicates the wavelength 655nm and the total span with this grating is 30nm from 640nm to 670nm as marked in figure 2(b). The intensity of each pixel along the bright line corresponds to the relative intensity of the spectrum at that particular wavelength and 100 frames of this spectrum image was acquired and averaged with 2-second exposure time at each temperature. Generally, the position and focus of the dots could shift due to thermal expansion effects. The stage was adjusted each time after heating so that every single quantum dot was at its original coordinates.

Figure 3 illustrates the typical normalized emission spectrum of a single QD when the substrate temperature changes from 17.2°C to 35.8°C. It is observed that the peak wavelength of the single quantum dot has a red shift (shift to bigger wavelength) as temperature increases. This peak wavelength shift was plotted in figure 4, where it is noted the measured temperature sensitivity of a single QD is 0.24nm/°C.

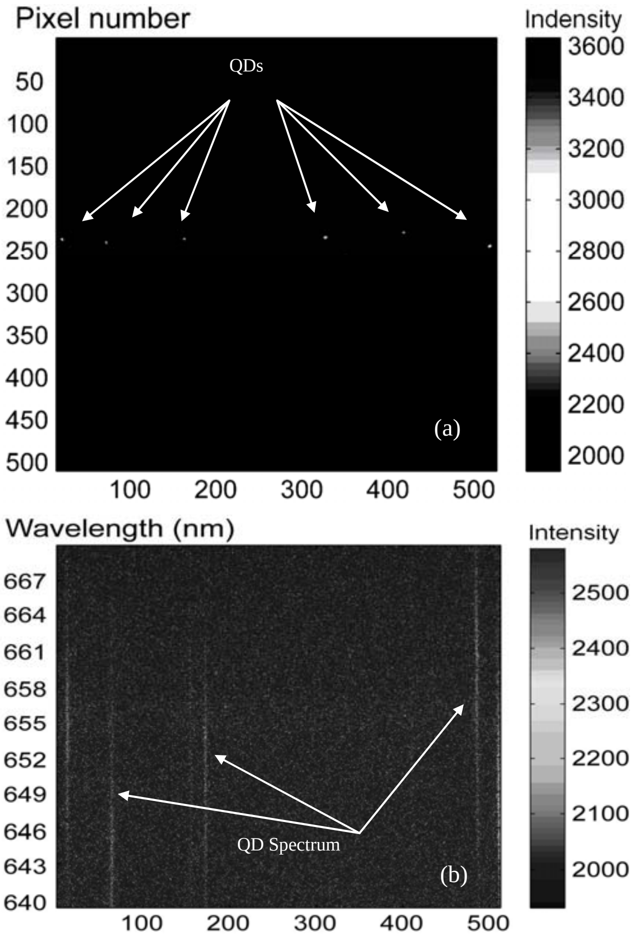

Fig. 2. (a) Examples of QDs under CCD and (b) emission spectrum of QDs.

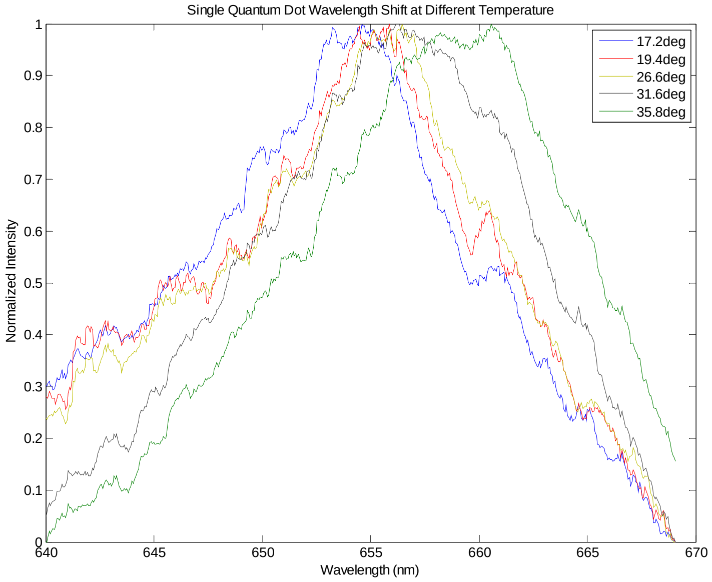

Fig. 3. The spectrum of a single QD from 17.2°C to 35.8°C.

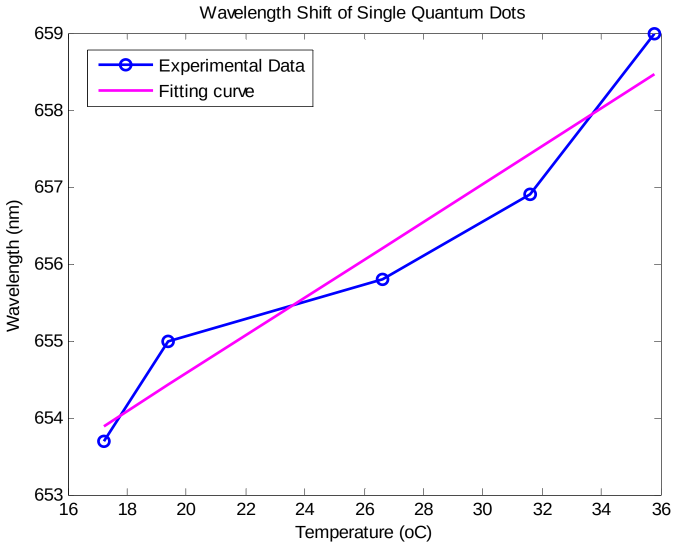

Fig. 4. Wavelength shift of a single QD versus temperature.

Temperature Measurement on MEMS heater

After the characterization of wavelength shift verse temperature of single quantum dot, the temperature profile along a MEMS heater was measured using the same spectrum detection technique with QDs deposited on the heater and compared with simulation results.

The MEMS heater was made of aluminum with dimension of $1000\times40\times0.1\mathrm{um}^3$ fabricated on top of a Pyrex wafer by evaporation and lift-off processes as shown in figure 5(a). It has two 1.5mm-in-diameter circular contact pads, where the wires were connected out by conductive epoxy (ITW Chemtronics). Afterwards, 3µl of 200pM 655-nm CdSe QD solution was applied and dried in air. The fluorescent picture of the microheater after quantum dot deposition is shown in Fig.5(b). The slit image can be seen clearly on both bright field and fluorescence pictures as shown. This slit was then controlled to a 30µm-wide opening, which corresponds to 500nm wide opening on the heater to confine the measurement range in the y direction during the experiment.

A 60× air objective with confocal microscopy setup was utilized in order to realize the non-contact measurement. Under this condition, the recorded image is only 118µm wide for each shot such that about 12 images have to been taken to cover the 1mm length of the heater with 100µm shift each time. Each pixel along the x orientation on the spectrum file corresponds to a physical spot on the heater and its spectrum reveals the local temperature value. The overlapped portions between images were averaged during the data analysis. For each set of spectrum recording, 10 frames of spectrum image were acquired with 1s exposure time. Different voltages were applied to heat the heater and the spectrum data were collected after the heater reached steady state. The temperature profile is calculated based on the sensitivity result from the aforementioned single QD experiment.

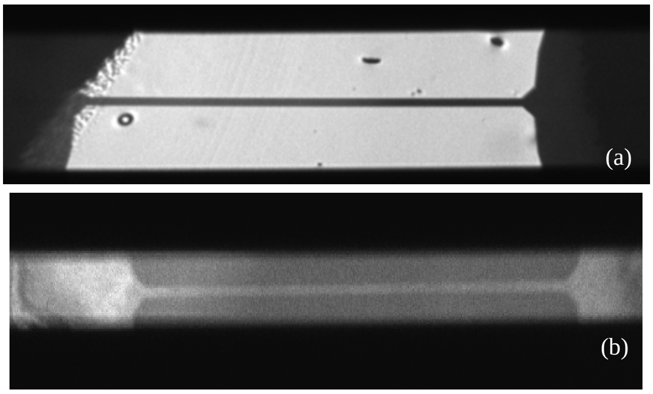

***Fig. 5.** (a) A bright field picture and (b) a fluorescent picture of the microheater after coating with QDs.*

Since the heater is a simple attached line-heater, the steady state temperature profile along the heater can be evaluated by the established analytical equation [6],

$$T(x) = T_r - (T_r - T_\infty)\frac{\cosh\left[\sqrt{\varepsilon}\left(x - \frac{L}{2}\right)\right]}{\cosh\left(\sqrt{\varepsilon}\,\frac{L}{2}\right)} \qquad (6)$$

Where T is the temperature along the micro heater; T_∞ is the ambient temperature, L is the total length of the heater; both ε and T_r are parameters that are functions of the structure dimensions, thermal properties, input current and the heat conduction shape factor [7].

Figure 6 illustrates the calculated temperature from spectrum measurement along the heater under different applied voltages as solid lines and the simulation results as dash lines. It can be observed that the trend of the temperature profile along the heater from the measurement correspond to the simulation results very well under different applied voltages. Figure 7 shows the difference between both data in the middle point of the heater with respect to the applied voltages and maximum variation is 0.8^{o}C.

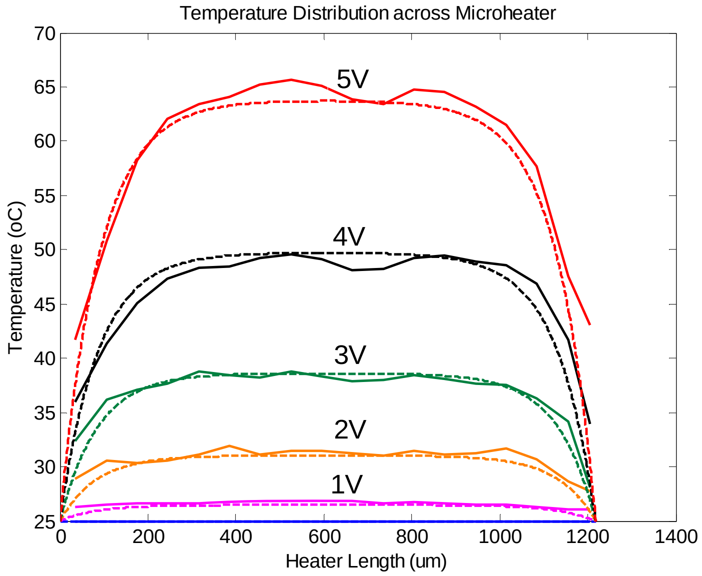

Fig. 6. Comparison of experimental data (solid lines) and simulation results (dash lines): temperature distribution for aluminum heater versus applied voltages.

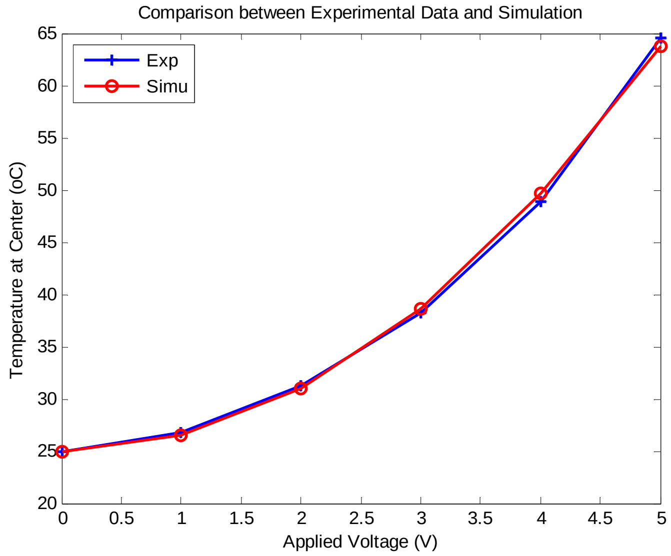

Fig. 7. Comparison of experimental and simulation results: temperature at the center of the microheater versus applied voltage.

The temperature profile in figure 6 was averaged over every 70µm to reduce the influence from the wavelength variation and the sample surface charge. However, potentially the spatial resolution of this detection technique can be extended to the numerical aperture of objective lens, which is 285nm for 60× air objective in the current setup. If the quantum dot deposition is diluted enough and the optical detection scheme can be further improved, the detection limit could be lower down to the single-quantum dot size.

Conclusions

The spectrum shift of a single quantum dot was successfully characterized under different temperatures as 0.24nm/^{o}C as the foundation for the measurement of temperature profiles for a MEMS heater in 25~65^{o}C range. Experimental and simulation results show great consistency. As such, this technique has the potential to be applied to micro/nano temperature measurements for both MEMS structures and biological samples.

Acknowledgement

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