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 1-mm long, 40-µm wide aluminum micro heater. Quantum dot emission wavelength shifts as a function of temperature was for the first time characterized at the single particle level to be 0.24 nm/°C in the 25–65 °C range. Temperature profiles of a MEMS heater under different input powers were evaluated based on the spectral shift of bulk quantum dots on the heater and were compared with a one-dimensional electrothermal model. Both experiments and simulations are consistent with variations of less than 0.8 °C. The theoretical spatial resolution of this technique can go down to the size of a single quantum dot for non-contact temperature characterizations of micro/nano structures including biological samples.

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

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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 a nominal size 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 use 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.

Fig. 1 shows schematically, how CdSe QDs with a nominal size of 15–20 nm in diameter can be used to detect temperature changes in a non-contact manner. A 532-nm green laser is used to excite the QDs on micro/nano devices or inside biological samples through a microscope (Olympus, IX71). The emission 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 500 nm) and recorded by an intensified Cascade Camera (512B, Roper Scientific). When the local temperature changes, the emission spectrum of QDs shifts and reports each QD's local temperature.

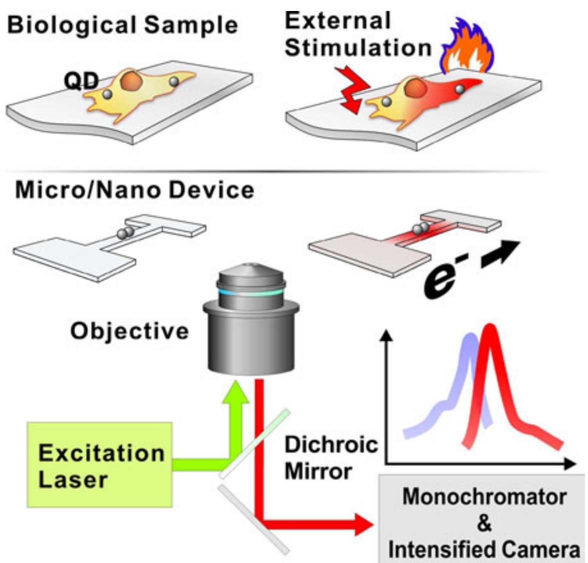

Fig. 1. The schematic diagram of non-contact temperature characterization using quantum dots by detecting their emission spectrum shifts.

Temperature Calibration

The commercially available CdSe quantum dots with a nominal emission wavelength at 655 nm (Qdots/Invitrogen) came encapsulated by a ZnS shell, coated with a layer of organic polymer, and conjugated with streptavidin. Experimentally, QDs solution was diluted in PBS (phosphate–buffered saline) to 0.5 pM. 20 µL of this dilution

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was sandwiched between two 24×50 mm^2 glass cover slips. After a period of 10-minute incubation at 100 ^{o}C, the cover slips were separated and 10 µL of PDMS (1:1 mixture of base and curing agent) was added on one cover slip to fix the position of QDs. Afterwards, a 22×22 mm^2 glass cover slip was covered on the sample and sealed by nail polish on the edges.

Total internal fluorescence reflection microscopy (TIRFM) was used to acquire the image and spectrum of individual quantum dot. The TIRF objective was 100× with a numerical aperture of 1.4. A thermocouple (5SC-TT-K-36-36, Omega Engineering, Inc.) was taped onto the top of small glass cover slip next to the observation point to monitor the local temperature.

The concentration of the quantum dot sample was kept low to optically resolve each single quantum dot as shown in Fig. 2(a), where about 10 single QDs were recorded in an area of 80×10 µm^2. A slit in the monochromator was utilized to minimize of the influence of other QDs outside the centerline region in the image. Then the wavelength of monochromator was set to 655 nm to disperse the spectrum of each single quantum dot inside the image view field into vertical lines as shown in Fig. 2(b). Because of the fluorescence intermittency, not all the quantum dots in Fig. 2(a) show their spectra in Fig. 2(b). With the total span of this grating being 30 nm, from 640 nm to 670 nm, the center of the image in the y axis indicates the wavelength 655 nm as marked in Fig. 2(b). The intensity of each pixel along the bright vertical lines corresponds to the relative intensity of the spectrum at that particular wavelength. 100 frames of this spectral image were 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. This was compensated by adjusting the sample mounting stage every time after heating so that every single quantum dot was at its original coordinates.

Fig. 3 illustrates the typical normalized emission spectrum of a single QD when the substrate temperature was increased from 17.2 ^{o}C to 35.8 ^{o}C. It was observed that the peak wavelength of single quantum dot exhibited a red shift (shift to greater wavelength) as temperature increases. This peak wavelength shift is plotted in Fig. 4, where it is noted the measured temperature sensitivity of a single QD is 0.24 nm/^{o}C.

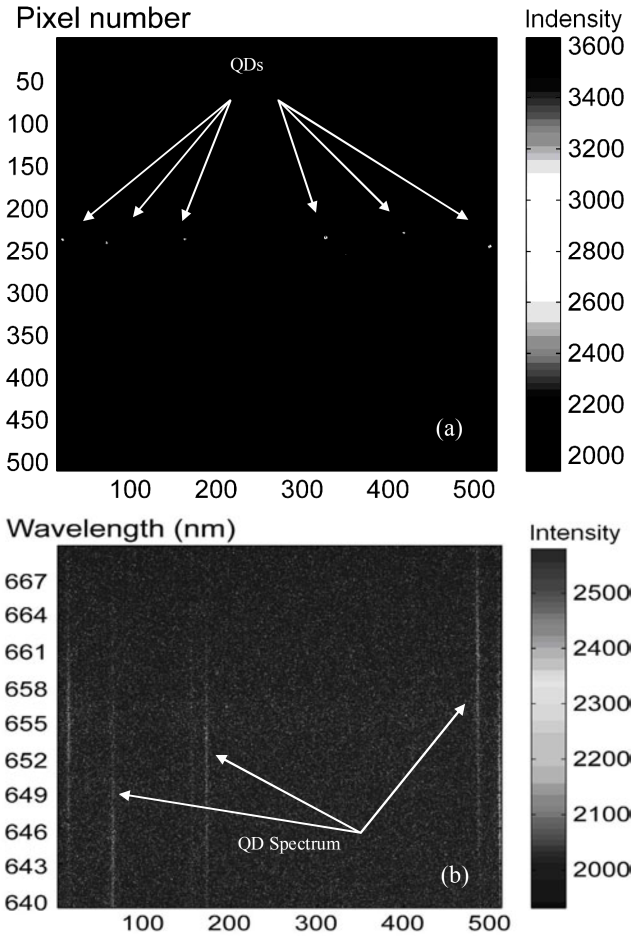

Fig. 2. *(a) Examples of QDs under CCD and (b) emission spectrum of QDs.*

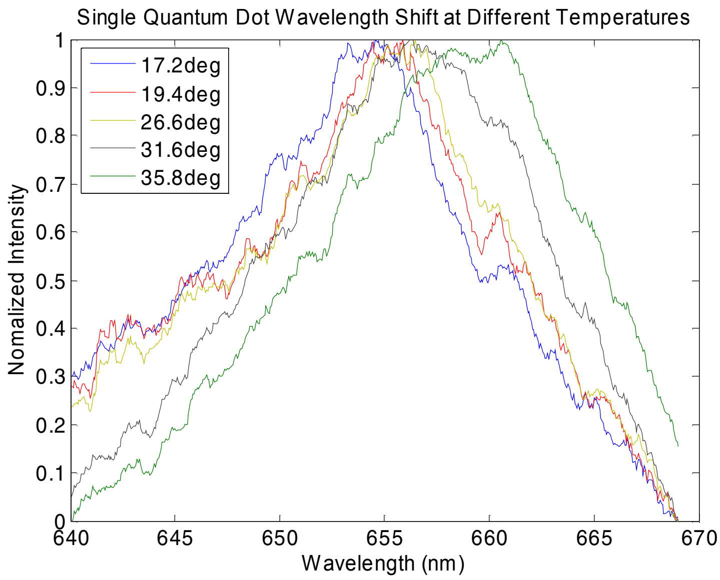

Fig. 3. *The spectrum of a single QD from 17.2 ^{o}C to 35.8 ^{o}C.*

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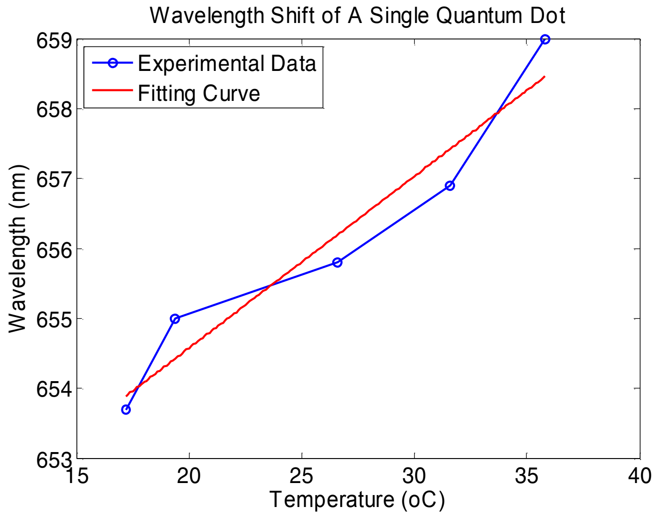

Fig. 4. *Wavelength shift of a single QD versus temperature.*

Temperature Measurement on MEMS heater

After the characterization of wavelength shift verse temperature of single quantum dots, the temperature profile along a MEMS heater was measured using the same spectral detection technique with QDs deposited on the heater. The results were compared with simulations.

The MEMS heater was made of aluminum with dimensions $1000 \times 40 \times 0.1\ \mu m^3$, fabricated on top of a Pyrex wafer by evaporation and lift-off processes as shown in Fig. 5(a). It has two 1.5-mm in-diameter circular contact pads, where the wires were connected out by conductive epoxy (ITW Chemtronics). Afterwards, 3 µL of 200-pM CdSe QD solution was applied and dried in air. The fluorescent image of the microheater after quantum dot deposition is shown in Fig.5(b). The slit can be seen clearly on both the bright field and the fluorescence image. This slit was then narrowed down to a 30 µm-wide opening, which corresponds to a 500 nm-wide stripe on the heater to confine the measurement range in the y direction during the experiment.

A 60× air objective was used to realize the non-contact measurement. Under this condition, the recorded image was only 118 µm wide for each shot such that about 12 images had to be taken to cover the entire 1-mm length of the heater with 100-µm shift for each frame. Each pixel along the x orientation on the resulting spectral image corresponds to a physical spot on the heater, with its spectrum revealing the local temperature value. The overlapped portions between images were averaged during the data analysis. For each set of spectrum recording, 10 frames of spectral image were acquired with 1-s exposure time. Different voltages were applied to heat the heater. The spectral data were collected after the heater reached steady state. The temperature profile was calculated based on the calibration results from the aforementioned single QD experiment.

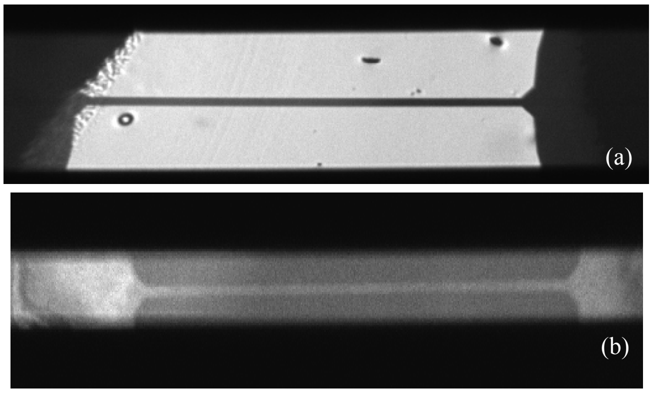

Fig. 5. *(a) A bright field picture and (b) a fluorescent picture of the microheater after coating with QDs.*

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's dimensions, thermal properties, input current, and the heat conduction shape factor [7].

Fig. 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. Fig. 7 shows the difference between the two data sets in the middle point of the heater with respect to the applied voltages and maximum variation is 0.8 °C.

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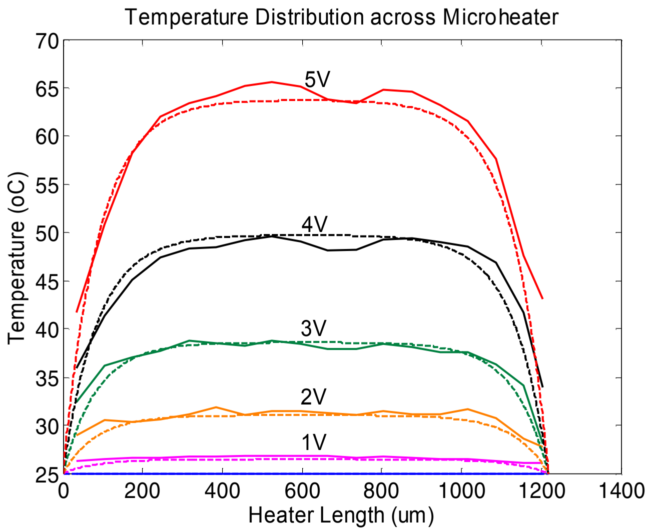

Fig. 6. *Comparison of experimental data (solid lines) and simulation results (dash lines): temperature distribution for aluminum heater versus applied voltages.*

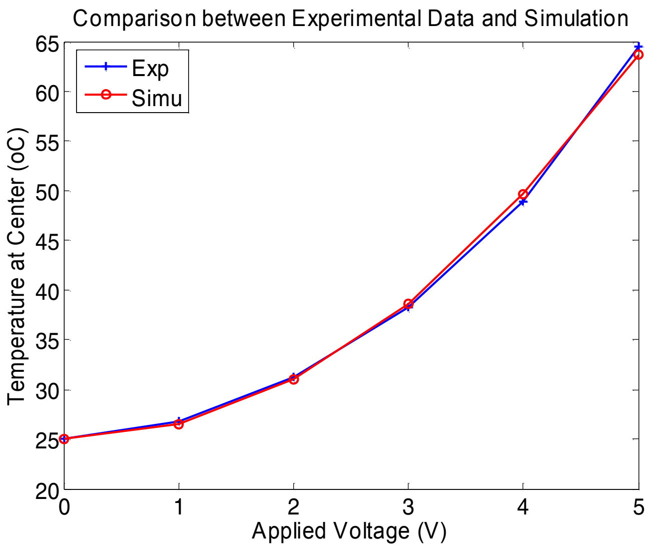

Fig. 7. *Comparison of experimental and simulation results: temperature at the center of the microheater versus applied voltage.*

The temperature profile in Fig. 6 was averaged over every 70 µm to reduce the influence from the wavelength variation, the sample surface charge, and other measurement-related noise. Nevertheless, in principle, the spatial resolution of this detection technique can be extended to the optical diffraction limit as defined by the numerical aperture of objective lens, which is 285 nm for a 60× air objective in the current setup. If the quantum dot deposition is dilute enough and the optical detection scheme can be further improved, the detection limit could be expanded to the single-quantum dot size.

Conclusions

The spectral shift of a single quantum dot was successfully characterized under different temperatures as 0.24 nm/°C and used as the basis for the measurement of temperature profiles for a MEMS heater in 25–65°C range. Experimental and simulation results showed great consistency. As such, this technique has the potential to be applied to non-contact micro/nano temperature measurements for both MEMS structures and biological samples.

Acknowledgement

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Reference

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