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Optically manipulated nanomechanics of semiconductor nanowires*

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Opto–electromechanical coupling at the nanoscale is an important topic in new scientific studies and technical applications. In this work, the optically manipulated electromechanical behaviors of individual cadmium sulfide (CdS) nanowires are investigated by a customer-built optical holder inside transmission electron microscope, wherein *in situ* electromechanical resonance took place in conjunction with photo excitation. It is found that the natural resonance frequency of the nanowire under illumination becomes considerably lower than that under darkness. This redshift effect is closely related to the wavelength of the applied light and the diameter of the nanowires. Density functional theory (DFT) calculation shows that the photoexcitation leads to the softening of CdS nanowires and thus the redshift of natural frequency, which is in agreement with the experimental results.

Keywords: opto–electromechanical coupling, nano-electromechanical systems (NEMS), *in-situ* transmission electron microscopy (TEM), semiconductor nanowires

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1. Introduction

The electromechanical resonances of individual one-dimensional nanostructures—i.e., the excitation of their natural mechanical resonances by alternating electric field—have been widely investigated due to their basic research of nanomechanics and potential applications in nanoelectromechanical systems (NEMS).[1–8] In the previous reports, mechanical parameters of a nanoresonator, such as resonance frequency, amplitude, and mechanical quality factor, can be modulated by electric field pulling,[9] nanoparticle attaching,[10,11] thermal effect,[12–14] etc. The nanogenerator was invented by using the coupling effect between piezoelectric and semiconducting properties of zinc oxide nanowires.[15] The output of a nanogenerator can be tuned by photo excitation.[16] The underlying principle of the devices is that the photoinduced extra charge carriers change the piezopotential and Schottky barrier height, where the coupling between light and mechanical property is fundamental. Several experiments were also carried out using the indentation method.[17] Atomic force microscopy (AFM) has been used to characterize the light illumination effect on the mechanical properties of nanowires. The important applications of optical effects on semiconductors, photoelectric materials and devices have been widely researched.[18,19] Recently, the coupling among optical, mechanical, and electronic properties of semiconductor nanostructures is arousing interest. The cavity nano-optomechanics experiments have been realized, in which the new method was developed for detecting and using the optically coupled nanomechanical motion.[20–26] It is also reported that the ZnO and ZnS nanobelts become hardened upon light illumination,[27,28] which is attributed to the surface oxygen ion process and electronic strain resulted from the photoinduced extra free carrier. So far, it is still a challenge to realize the optical modulation on electromechanical properties in dynamic state and at nanoscale.

In this work, we demonstrate the opto–electromechanical coupling effect of individual semiconductor nanowires at their vibration state, which is directly imaged inside a transmission electron microscope (TEM). We report the observation of redshift of the natural mechanical frequency of individual cadmium sulfide (CdS) nanowires under light illumination with photon energies larger than the band gap of CdS. The natural resonance frequency of CdS nanowires largely decreases under light illumination, which is closely related to the wavelength of the applied light and the diameter of the CdS nanowires. First-principles density functional theory (DFT)

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calculation shows that the photogeneration of free carriers accounts for the softening of CdS nanowires and thus the redshift of resonance frequency, which reveals the fundamentals of the coupling effect between optical and electromechanical properties.

2. Experimental

CdS nanowires (NWs) were synthesized by gold-catalyzed chemical vapor deposition method.[29] The electromechanical measurements were carried out inside a transmission electron microscope equipped with an optical holder. The holder was specially designed with a $\phi = 2$ mm optical fiber for illuminating the sample. A piezo-driven slider was used for precisely positioning the tungsten electrode. The nanowire was placed on a gold wire by dipping the gold wire on CdS nanowire arrays. An electrochemically sharpened tungsten tip was used to form the counter electrode. The tungsten tip was driven to the nanowire and welded together by electron irradiation induced carbon deposition to form a strong bonding.[30] Then the tungsten tip was driven back with the bonded nanowire from the gold wire. By connecting the two electrodes to the external measurement device, a bias could be applied across nanowires. For nanowires with moderately high aspect ratio, the mechanical resonance could be induced by applying an alternating current (AC) bias.[31]

3. Results and discussion

3.1. *In situ* TEM experiments

Figure 1(a) shows the scheme of the *in situ* TEM electromechanical system. A stationary nanowire (Fig. 1(b)) can be regarded as a vibration cantilever clamped at one end. By adjusting the frequency of the applied AC bias, the resonance can be excited, as shown in Figs. 1(c) and 1(d). The resonance frequency depends on the Young's modulus and the specific size of the nanowire according to the following equation:

$$f_j = \frac{\beta_j^2 D}{8\pi L^2}\sqrt{\frac{Y}{\rho}}. \tag{1}$$

Here, D, L, Y and ρ are diameter, length, Young's modulus, and mass density of the nanowire, respectively. β_j stands for the constant for the jth harmonic vibration with $\beta_1 = 1.875$ and $\beta_2 = 4.694$. This equation results from the Bernoulli–Euler analysis of cantilevered elastic beams.[32] The diameter and length of the nanowires can be measured directly by TEM image. When the fundamental resonance frequency f is found, the Young's modulus of nanowire can be determined.

It is crucial to find the correct fundamental resonance frequency f to obtain the Young's modulus.[33] In our experiments, the applied frequencies of AC bias are adjusted in a large range and checked with the higher order harmonic resonance mode. Figures 1(c) and 1(d) show the first and second harmonic resonance modes, and their resonance frequencies are $f1 = 263.4$ kHz and $f2 = 1656$ kHz, respectively. $f2/f1 = 6.3$ is close to the theoretical ratio 6.2,[32] indicating a uniform cantilevered beam. The node position of the second harmonic resonance is 0.79 L, in good agreement with the theoretical value 0.78 L.[32] In this way, the fundamental resonance frequency can be correctly secured. Figure 1(e) shows another resonant nanowire. The resonance amplitude is kept moderately small to avoid nonlinear effects. Figure 1(f) gives the corresponding resonance peak, fitted by a Lorentzian curve. Using the full width at half maximum (FWHM) of the fitted Lorentz curve as Δf, the mechanical quality factor Q can be determined.[34] For the resonant nanowire in Fig. 1(e), its mechanical quality factor is 538.

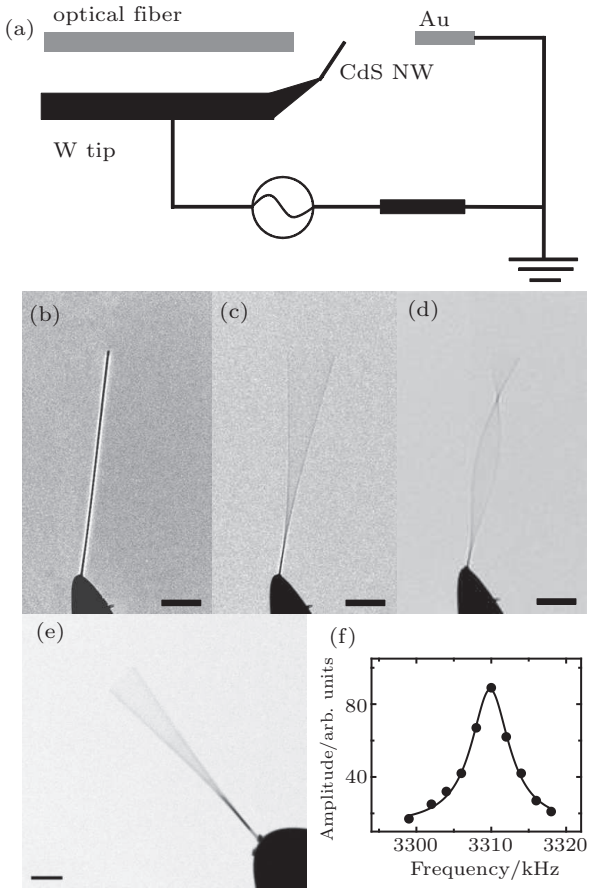


Fig. 1. Experimental setup and nanowire resonators. (a) Scheme of the *in situ* TEM fiber-assembled electromechanical holder. (b)–(d) A selected stationary nanowire, its first harmonic resonance mode, and second harmonic resonance mode, respectively. Scale bar: 2 μm. (e) and (f) A vibrating nanowire with moderately small resonance amplitude, and its resonance peak fitted by Lorentzian line. Scale bar: 2 μm.

Using the *in situ* TEM optical holder, the light is introduced through the optical fiber, so the nanowire can be illuminated. The optical system is equipped with five light sources with the wavelengths at 405 nm, 445 nm, 532 nm, 655 nm, and 910 nm, respectively. A Si power meter from Thorlabs is used

to measure the light power. When light illumination is applied onto the CdS nanowire, the change of resonance frequency can be obtained. A series of experiments have been carried out to show the process that light affects the resonance frequency. In the experiments, a 405 nm laser is used to illuminate the sample. The light intensity on the nanowire is measured to be approximately 16 mW/cm^2. The four pictures in Fig. 2 show a series of operations. At the beginning, the resonance state is found in darkness and the resonance frequency is measured to be 2106 kHz. Then the shutter is open and light is illuminated onto the nanowire. At the same time, the resonance disappears, as shown in Fig. 2(b). Then, tuning the AC frequency down to 2086 kHz, the resonance appears, as shown in Fig. 2(c). When the light shutter is closed, the resonance disappears again, as shown in Fig. 2(d). The whole experiment is reversible and repeatable. This experiment demonstrates a redshift effect of the resonance frequency upon light illumination.

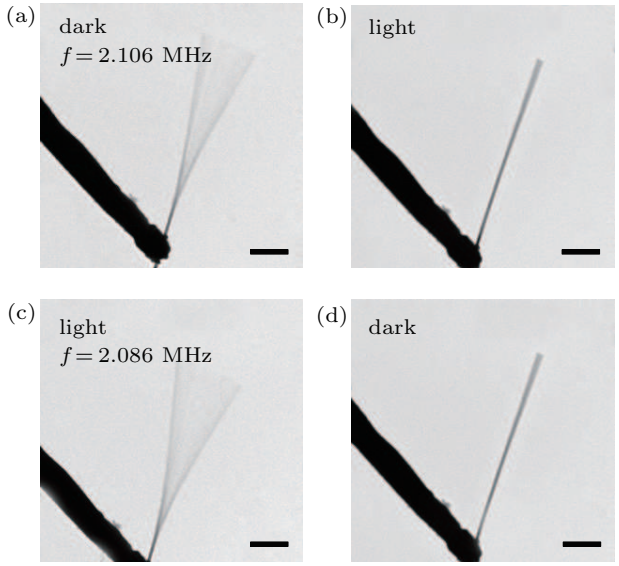


Fig. 2. Resonance frequency shift of a CdS nanowire induced by light illumination. (a)–(d) show that the light illumination lowers the resonance frequency from 2106 kHz to 2086 kHz. (a) Resonance at $f = 2106$ kHz under darkness; (b) resonance disappears under light illumination (wavelength is 405 nm); (c) resonance appears again by tuning frequency to $f = 2086$ kHz under light illumination; (d) resonance disappears after turning off light illumination. Scale bar: 1 μm.

We further perform the resonance frequency response measurements using five different laser sources. A constant power intensity of 16 mW/cm^2 is set for the five lasers in the experiment. The laser wavelengths are 405 nm, 445 nm, 532 nm, 655 nm, and 910 nm, respectively. The results are plotted in Fig. 3(a). Note that only light with wavelength less than 515 nm could induce frequency shift, and there is no frequency shift when the wavelength of the illuminating light is 655 nm or 910 nm. Moreover, to elucidate the origin of the frequency shift, a room temperature photoluminescence (PL) measurement of CdS nanowires is carried out. As shown in Fig. 3(a), the PL peak centers at 515 nm, corresponding to the band-edge emission of the CdS nanowire. It is noted that the resonance frequency shift drops quickly as the wavelength of the applied light source increases. The dependence of the frequency shift on light power for a CdS nanowire is shown in Fig. 3(b). For the light illumination with wavelengths of 445 nm and 405 nm, the natural frequency shift increases with increasing light power, while no frequency change is found for the light illumination with a wavelength of 655 nm, even at much higher light power. This also confirms that the optically modulated electromechanical behavior of CdS nanowires is highly sensitive to the applied light wavelength.

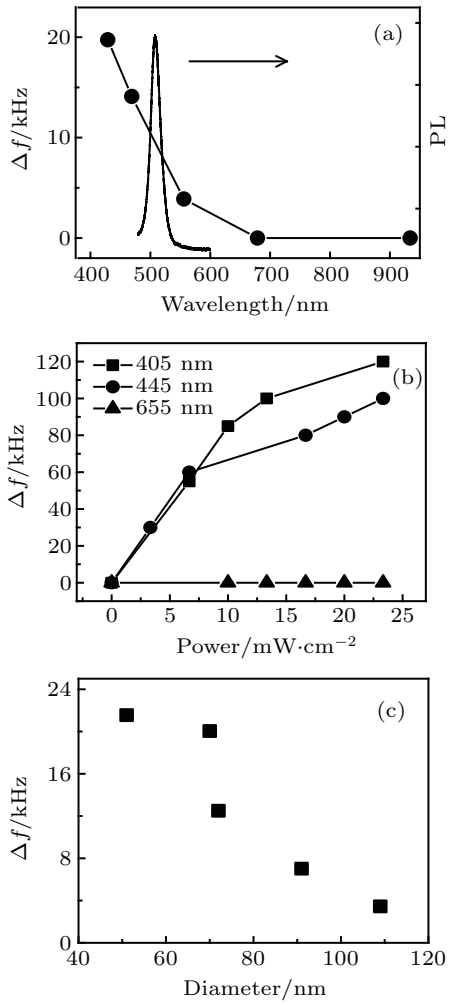


Fig. 3. The dependence of resonance frequency shift on the applied light wavelength, power intensity, and nanowire diameter. (a) The redshift of resonance frequency increases with decreasing light wavelength, while no frequency shift is found for the light with wavelengths of 655 nm and 910 nm. The inset is PL spectrum of CdS nanowire for reference. (b) The redshift of resonance frequency increases with increasing light power, while no frequency shift is found for the light illumination with wavelength of 655 nm even at much higher light power. (c) The redshift of resonance frequency becomes larger for CdS nanowires with smaller diameters (light source: wavelength 405 nm, power: 16 mW/cm^2).

The thermal effect due to light illumination has been considered in this work. According to Eq. (1), the decrease in fundamental frequency indicates the decrease of Young's modu-

lus. It is known that a temperature rise can cause Young's modulus decrease. Under a typical light illumination with a power intensity of 16 mW/cm^2 in our experiments, the temperature rise of nanowire is estimated to be on the order of 1 K (see the details in Supplementary Material Sections S2–S5). In the meantime, the Young's modulus measured in our experiment ranges from several tens to several hundreds of GPa, while the temperature coefficient of Young's modulus for CdS is about -17 MPa/K at 300 K,[35] so the relative decrease of Young's modulus due to thermal effect is estimated as about 10^{-4}, which is much smaller than our observation by 2 orders of magnitude. Therefore, the thermal effect is not the dominant factor for the redshift of resonance frequency in this study. Based on the light wavelength and power dependence, the resonance frequency shift should be closely related to the photoexcitation in CdS nanowire. Furthermore, the effect of light illumination on frequency shift for metallic nanowires and the nanowires with large bandgap has been examined. It is shown that their resonance frequencies remain stable while turning on/off the light illumination (see Supplementary Material Section S1). This confirms that it is the photoexcitation rather than the thermal effect that dominates the opto–electromechanical coupling in the semiconductor nanowires.

Additionally, the redshift of resonance frequency for CdS nanowires with different diameters is examined. We choose the 405 nm laser as the light source and keep a constant power of 16 mW/cm^2. As shown in Fig. 3(c), a smaller diameter leads to a larger frequency shift in resonance frequency. This means that the opto–electromechanical coupling becomes much stronger for the nanowires with smaller diameters, showing a remarkable size effect. Interestingly, the CdS nanowires with smaller diameters become much "softer" under light illumination, in contrast to the usual size effect; i.e., the thinner nanowires become harder.[33,34,36] This phenomena verifies that the softening behavior under light illumination is an intrinsic property of CdS nanowires, which should be originated from the photoexcitation of CdS semiconductor.

3.2. DFT calculation

The DFT calculation has been carried out to explain the photoexcitation modulated nanomechanics. CdS nanowires are investigated using DFT within the generalized gradient approximation (GGA) by Perdew–Burke–Ernzerhof (PBE) functional. The projector-augmented wave potentials are used, as implemented in the Vienna *ab initio* simulation package. A plane-wave cutoff of 400 eV and a Monkhorst–Pack $\boldsymbol{k}$-point meshes of $1 \times 1 \times 5$ per unit cell are adopted. Sufficient vacuum space of more than 20 Å is inserted between surfaces of nanowires to minimize the interaction between periodic images. Structure optimizations are performed with a convergence threshold of 0.01 eV/ Å on the interatomic forces. We study the [0001] CdS nanowires surrounded by the low free energy $(0\bar{1}10)$ facets, which form two hexagonal cross sections with a diameter of 1.2 nm, as shown in Fig. 4(a). To account for the effects of light illumination, the excess photogenerated electrons or holes are introduced into the nanowires. We have calculated six doped states, namely: neutral state; positive-doped states with one and three excess holes; and negative-doped states with one, two, and three excess electrons, respectively.

The Young's modulus of a CdS nanowire can be calculated by the equation

$$Y = \frac{1}{V_0} \times \left(\frac{\partial^2 E}{\partial^2 \varepsilon} \right)_{\varepsilon=0}. \tag{2}$$

Here, E is the total energy of nanowire with an axial strain ε, and V_0 is the equilibrium volume. The nanowires are gradually elongated and compressed along the axial direction, within a small strain range from -2% to $+2\%$ around the equilibrium structure. After the structure optimizations, the Young's modulus is obtained by a quadratic polynomial fit of the E–ε data. The length, cross-section area, total volume, and Young's modulus of the nanowire with different carrier densities are shown in Table 1.

Table 1. The result of DFT calculations.

	Neutral	1 electron	2 electrons	3 electrons	1 hole	3 holes
Length/Å	6.85	6.90	6.94	6.96	6.82	6.80
Area/Å^2	97.8	97.8	97.8	97.9	98.7	100.7
V_0/Å^3	669.9	674.8	678.4	679.3	673.1	684.8
Y/GPa	101.2	95.7	90.5	88.3	89.6	85.5

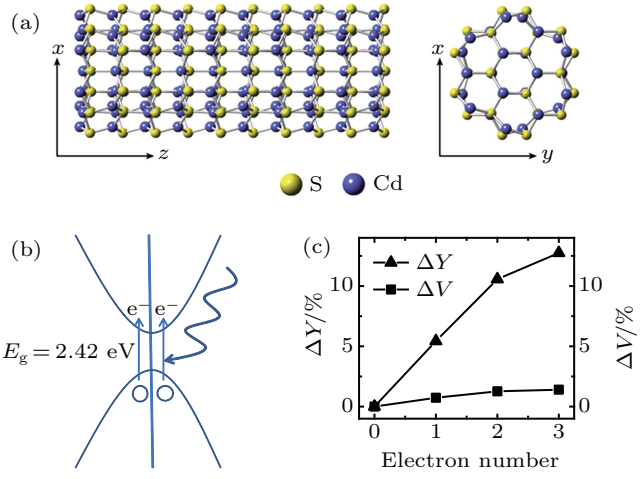


Fig. 4. The DFT calculation on the photoexcitation effect of Young's modulus of CdS nanowires. (a) The crystal structure of CdS nanowire. The nanowire is along the c axis and with $(0\bar{1}10)$ side surface. (b) Illustration of the charge carrier injection process; under illumination with photon energy larger than the band gap of CdS, electrons will be excited from the valence band to the conduction band. (c) Relative changes of Young's modulus and volume at different injected electron numbers.

It can be found that the Young's modulus becomes smaller with doping of excess electrons or holes. More free charges lead to even smaller Young's modulus. This result fits

our experimental result very well. This process is illustrated in Fig. 4(b). The electrons in the conduction band and the holes in the valence band form extra carriers, which will lower the Young's modulus of the nanowire. The total volume of the nanowire is also related to the injected charge, as shown in Fig. 4(c). However, the relative change of Young's modulus is larger than the change rate of volume. This excludes the possibility that the volume change dominates the decrement of Young's modulus. The injected charge carriers will weaken the chemical bond connecting Cd and S atoms and hence decrease the Young's modulus of CdS nanowire. The decrement of Young's modulus results in the natural frequency change, as shown in Eq. (1).

4. Conclusions

In summary, a photoexcitation induced opto–electromechanical coupling effect in CdS nanowires has been investigated by *in situ* TEM method. It is found that the natural frequencies of CdS nanowire resonators under light illumination with photon energies larger than the band gap of CdS become considerably smaller than those under darkness. The redshift of electromechanical resonances is dependent on the wavelength of the applied light and the diameter of the nanowires. DFT calculation shows that the photogeneration of free carriers leads to in the softening of CdS nanowires and thus the redshift effect of natural frequency. The remarkable coupling effect between optical and mechanical properties of semiconductor nanowires suggests their potential applications in optical sensors and the opto–nanoelectromechnical system.

References

[1] Craighead H G 2000 *Science* **290** 1532
[2] Poncharal P, Wang Z L, Ugarte D and De Heer W A 1999 *Science* **283** 1513
[3] Gao R, Wang Z L, Bai Z, de Heer W A, Dai L and Gao M 2000 *Phys. Rev. Lett.* **85** 622
[4] Masmanidis S C, Karabalin R B, De Vlaminck I, Borghs G, Freeman M R and Roukes M L 2007 *Science* **317** 780
[5] Feng X L, He R, Yang P and Roukes M L 2007 *Nano Lett.* **7** 1953
[6] Feng X L, White C J, Hajimiri A and Roukes M L 2008 *Nat. Nanotechnol.* **3** 342
[7] Kozinsky I, Postma H W C, Bargatin I and Roukes M L 2006 *Appl. Phys. Lett.* **88** 253101
[8] Pickering E, Bo A, Zhan H, Liao X, Tan H H and Gu Y 2018 *Nanoscale* **10** 2588
[9] Purcell S T, Vincent P, Journet C and Binh V T 2002 *Phys. Rev. Lett.* **89** 276103
[10] Dohn S, Svendsen W, Boisen A and Hansen O 2007 *Rev. Sci. Instrum.* **78** 103303
[11] Jensen K, Kim K and Zettl A 2008 *Nat. Nanotechnol.* **3** 533
[12] Okamoto H, Ito D, Onomitsu K and Yamaguchi H 2008 *Phys. Status Solidi C* **5** 2920
[13] Lobato-Dauzier N, Denoual M, Sato T, Tachikawa S, Jalabert L and Fujita H 2019 *Ultramicroscopy* **197** 100
[14] Roy A, Ju S, Wang S and Huang H 2019 *Nanotechnology* **30** 065705
[15] Wang Z L and Song J 2006 *Science* **312** 242
[16] Lin Y, Song J, Ding Y, Lu S and Wang Z L 2008 *Adv. Mater.* **20** 3127
[17] Wolf B, Meyer D, Belger A and Paufler P 2002 *Philos. Mag. A* **82** 1865
[18] Teng F, Hu K, Ouyang W and Fang X 2018 *Adv. Mater.* **30** 1706262
[19] Das S, Hossain M J, Leung S F, Lenox A, Jung Y, Davis K, He J H and Roy T 2019 *Nano Energy* **58** 47
[20] Favero I, Stapfner S, Hunger D, Paulitschke P, Reichel J, Lorenz H, Weig E M and Karrai K 2009 *Opt. Express* **17** 12813
[21] Stapfner S, Ost L, Hunger D, Reichel J, Favero I and Weig E M 2013 *Appl. Phys. Lett.* **102** 151910
[22] Liu Y L, Wang C, Zhang J and Liu Y X 2018 *Chin. Phys. B* **27** 024204
[23] Stapfner S, Favero I, Hunger D, Paulitschke P, Reichel J, Karrai K and Weig E M 2010 *SPIE Photonics Europe*, April 12–16, 2010 Brussels, Belgium, Vol. 7727, p. 772706
[24] Favero I and Karrai K 2008 *New J. Phys.* **10** 95006
[25] Jiang C, Cui Y S, Liu H X, Li X W and Bin G 2015 *Chin. Phys. B* **24** 054206
[26] Qin L G, Wang Z Y, Ma H Y, Wang S M and Gong S Q 2017 *Chin. Phys. B* **26** 128502
[27] Zhao M H, Ye Z Z and Mao S X 2009 *Phys. Rev. Lett.* **102** 45502
[28] Zheng X J, Yu G C, Chen Y Q, Mao S X and Zhang T 2010 *J. Appl. Phys.* **108** 94305
[29] Pan A, Liu R, Yang Q, Zhu Y, Yang G, Zou B and Chen K 2005 *J. Phys. Chem. B* **109** 24268
[30] Jin C H, Wang J Y, Chen Q and Peng L M 2006 *J. Phys. Chem. B* **110** 5423
[31] Gao P, Liu K, Liu L, Wang Z, Liao Z, Xu Z, Wang W, Bai X, Wang E and Li Y 2010 *J. Electron Microsc.* **59** 285
[32] Meirovitch L 1986 *Elements of Vibration Analysis* (2nd edn.) (New York: McGraw-Hill) pp. 204–227
[33] Chen C Q, Shi Y, Zhang Y S, Zhu J and Yan Y J 2006 *Phys. Rev. Lett.* **96** 75505
[34] Wang L, Tian X, Yang S, Xu Z, Wang W and Bai X 2012 *Appl. Phys. Lett.* **100** 163110
[35] Adachi S 2005 *Properties of Group-IV, III–V and II–VI Semiconductors* (Chichester: John Wiley & Sons) pp. 41–62
[36] Calarco R, Marso M, Richter T, Aykanat A I, Meijers R, Hart A V D, Stoica T and Lüth H 2005 *Nano Lett.* **5** 981