BRIEF COMMUNICATION



Effects of Voltage and Temperature on Photoelectric Properties of Rolled-Up Quantum Well Nanomembranes

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Abstract

Rolled-up quantum well (QW) nanomembranes with different diameters are prepared using the lift-off method. The structural evolution and the influences of voltage and temperature on the photoelectric properties of the nanomembranes are investigated. We find that a QW in tensile status can enhance the photorepsonse by about 2.1 times, and a QW in compressive status leads to a decrease of photorepsonse to ~ 65%. With increasing temperature, the gap between the ground state and excited state in the conduction band decreases with a rate of ~ 0.008 meV/K and the thermal effect mainly affects the shift of conduction band. For a working rolled-up device, the change of band gap due to the thermal effect from the applied voltage is negligible.

Keywords Rolled-up nanomembrane \cdot energy band \cdot photorepsonse \cdot thermal effect

Introduction

Rolled-up nanotechnology is nanofabrication, which mainly adopts the traditional lift-off method.¹ The unfolded nanomembrane can be curled into micrometer- or nanometer-scale tubular structures taking the advantage of the internal strain of the nanomembrane.^{2–5} Quantum well infrared photo-detectors (QWIPs) are important application instances of this technology. The flexible nanomembrane containing quantum wells (QWs) is rolled up into a tubular structure, which can effectively expand the detection angle without much attenuation. The unique structure can greatly promote the quantum efficiency of QWIP compared with an unfolded nanomembrane due to the internal light reflection or optical

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resonance in the microtubular cavities.^{6–9} However, the band structure of a rolled-up nanomembrane can inevitably be modulated because of the shape change and the corresponding strain evaluation, which further affects the physical properties.^{10–16} Previously, the effects of some factors (e.g. strain) on the photoelectric properties of the rolled-up QWIPs have been studied in the literature.^{17–20} However, there are few studies on the effects of applied voltage and temperature on the band structure or the photoelectric properties, and they are urgently needed.

In this paper, we analyze the photoelectric properties of rolled-up QWIPs containing GaAs/AlGaAs QWs under different applied voltages and operating temperatures and find the band shift changes with applied voltage and temperature. We disclose the underlying mechanism and provide supplements and theories to QWIP-related fields, which will facilitate the fabrication of high-performance rolled-up QWIPs.

Experimental

The nanomembranes were deposited on GaAs (100) substrate by molecular beam epitaxy. From bottom to top, the deposited layers were, respectively, buffer layer (200 nm GaAs), sacrificial layer (30 nm AlAs), stress layer (20 nm $In_{0.2}Al_{0.2}Ga_{0.6}As$), bottom electrode layer (50 nm GaAs), QW layers (GaAs (6.5 nm)/Al_{0.26}Ga_{0.74}As (30 nm)) with two cycles, and upper electrode layer (20 nm GaAs). The electrode was a AuGe/Ni/Au (50 nm/25 nm/150 nm) layer. The released nanomembrane rolled up due to the strain introduced by the $In_{0.2}Al_{0.2}Ga_{0.6}As$ layer as the AlAs sacrificial layer was etched away.²¹ In this work, we fabricated rolled-up tubes with diameters of 62 and 150 μ m by removing the sacrificial layer in 10% and 15% dilute HF solutions, respectively.

High-resolution diffraction analysis of hard x-ray (0.6888 Å) was conducted using the hard x-ray micro-focusing beamline (BL15U1) of the Shanghai Synchrotron Radiation Facility (SSRF), and the spot size was about $2 \times 2 \mu m^2$. Photocurrent spectra at 10 K, 40 K, and 70 K were obtained using a Fourier transform infrared spectrometer (Nicolet 6700). Constant voltages of -3 V and -4.5 V were applied to study the effect of the voltage on the rolled-up device. The horizontal and vertical displacements of the sample under different applied voltages were measured by optical microscopy with an accuracy of 0.01 μ m.

Results and Discussion

It has previously been illustrated that both tensile and compressive strains co-exist in the nanomembrane, and there is a boundary between the tensile and the compressive regions called a neutral line (Fig. 1a).⁷ The layers at different sides of the neutral line are in different strain statuses. According to the x-ray diffraction (XRD) patterns in Fig. 1b, it can be seen that the diffraction peaks are different for rolled and flat nanomembranes. In the case of a flat nanomembrane, the diffraction peaks are from layers consisting of different materials, as introduced in the experimental part. The peak separation of the rocking curves for (200), (400), and (110) reflections results from the difference of lattice constants of



the epitaxial layers.²² Because GaAs has a sphalerite crystal structure,²³ the (110) reflection can be determined to be the Bragg diffraction of two different kinds of atoms connected with chemical bonds (Fig. S1), and the other two reflections correspond to Bragg diffraction of face-centered cubic lattices formed by identical atoms (Ga or As atoms) (see Supplementary Material equations S1-S7). For the rolled-up nanomembrane, the layers are in different strain statuses compared with the flat nanomembrane. Therefore, the change of the crystal lattice leads to shifts of diffraction peaks. It can be seen from Fig. 1b that (200) and (400) peaks weaken or even disappear after rolling. This may be because the spacing between atoms without the connection of chemical bonds is irregularly changed after rolling. Figure 1b also shows that the (110) peaks of GaAs, Al_{0.26}Ga_{0.74}As, and In_{0.2}Al_{0.2}Ga_{0.6}As layers are broadened to merge with each other. Specifically, in the rolled structure, the strain gradient in the nanomembrane leads to a continuous change of the spacing between atoms connected with chemical bonds, and as a result, only a broad diffraction peak can be observed.

From the viewpoint of an infrared detector, the influence from applied voltage and working temperature should be carefully investigated. Here, we measured the temperaturedependent photocurrent spectra of a rolled-up nanomembrane under different applied voltages. It can be seen from Fig. 2a that the sample has the strongest photocurrent at 40 K compared with the spectra obtained at 10 and 70 K. It has been demonstrated that QW_1 is under tensile strain and QW_2 is under compressive strain.⁷ Here, for photocurrent spectra under different applied voltages (Fig. 2b, c, and d), one can see that the peak intensities related to QW_1 under tensile strain are obviously higher than those related to QW_2 under compressive strain at 40 K, indicating that the photocurrent response of QW under tensile strain is promoted. It can be calculated from Fig. 2b, c, and d that the peak area of



Fig.1 (a) Schematic diagram of a rolled-up QWIP. The bottom is GaAs substrate, and the red curve is the neutral line which is the boundary between the tensile and the compressive regions. The outer surface of the tube is tensilely strained, while the inner surface is compressively strained. By removing the AlAs layer (orange), the

above nanomembrane rolls up to release the internal strain. The magnified part shows the QWs with tensile QW₁ and compressive QW₂. (b) High-resolution XRD patterns of rolled-up nanomembrane (diameter: 150 μ m) and flat nanomembrane. The horizontal axis represents the relative Bragg angle.





Fig.2 (a) Photocurrent spectra of a rolled-up nanomembrane (diameter Φ : 62 μ m) under different applied voltages (350, 400, and 450 mV), collected at different temperatures (10, 40, and 70 K). The following figures are photocurrents of rolled-up nanomembranes

(40 K, diameter Φ : 62 μ m) under voltages of (b) 350 mV, (c) 400 mV, and (d) 450 mV. Each spectrum can be divided into two sub-peaks originating from the two QWs.

Table I Photocurrent peak areas of QW_1 and QW_2 (i.e., A_{QW1} , A_{QW2} respectively) for rolled-up nanomembrane under different biases

	350mV	400 mV	450 mV
A _{QW1}	172	194	175
$A_{\rm QW2}$	53	61	66
$A_{\rm QW1}/A_{\rm QW2}$	3.2	3.2	2.7

 $QW_1 (A_{QW1})$ is larger compared with that of $QW_2 (A_{QW2})$. Quantitatively, the peak areas of QW_1 and QW_2 are listed in Table I. For samples under applied voltages of 350, 400, and 450 mV, the ratios of $A_{QW1(tensile)}/A_{QW2(compressive)}$ are 3.2, 3.2, and 2.7, respectively. Therefore, we should try to make the QW in tensile strain in order to enhance the photoresponse.

Figure 3 shows that, under different applied voltages at 40 K, the photocurrent spectra of the 45° edge-facet flat nanomembrane have no observable sub-peaks (QW₁ and QW₂), indicating that the two sub-peaks overlap for the flat nanomembrane, which is different from spectra of the rolled-up nanomembrane (diameter Φ : 62 μ m) with sub-peaks (see also Fig. 2). Obviously, the peak wavelength of



Fig. 3 Photocurrent spectra of a rolled-up nanomembrane (diameter Φ : 62 μ m) and the 45° edge-facet flat nanomembrane under different bias voltages (350, 400, and 520 mV), collected at 40 K.

the 45° edge-facet flat nanomembrane with compressive strain (9.60 μ m) is between those of QW₂ with compressive strain (9.40 μ m) and QW₁ with tensile strain (9.75 μ m) in a rolled-up nanomembrane. From Fig. 2, a redshift in the photocurrent peak of tensile QW₁ is apparent with regard

to compressive QW_2 , suggesting that the tensile strain can cause a redshift and the compressive strain causes a blueshift. Therefore, it is reasonable to conclude that, after rolling of the flat nanomembrane, one QW (i.e., QW₂) with increasing compressive strain causes the peak blueshift $(9.60-9.40 \ \mu m)$ in the photocurrent. On the other hand, the photocurrent peak of the other QW (i.e., QW₁) has a redshift $(9.60 \,\mu\text{m} \text{ to } 9.75 \,\mu\text{m})$ due to the transition from compressive to tensile status. The demarcation line between tensile and compressive regions after rolling is the neutral line, which was previously calculated to be at 58.5–61 μ m from the top.⁷ We also noticed that the areas of photocurrent peaks of both QW_1 and QW_2 are 93.2 for a flat nanomembrane under the applied voltage of 400 mV. Compared with the data shown in Table I, the photoresponse of QW₁ increases to 2.1 times due to the tensile strain therein. In contrast, the photoresponse of QW_2 decreases to about 65% caused by the increased compressive strain.

It is clear in Fig. 2a that for spectra collected at 10 K, 40 K, and 70 K, the photocurrent peaks of QW1 are at 9.74712 μm, 9.76547 μm, and 9.78390 μm, respectively. The redshifts of the photocurrent spectra are 0.000239 eV for a temperature change of every 30 K. Because the QWIP is n-type, one may infer that the gap between the ground state and excited state in the conduction band decreases with a rate of ~ 0.008 meV/K. Furthermore, according to previous literature, the change of band gap caused by the thermal effects is ~ 0.45 meV/K.²⁴ Therefore, the thermal effect mainly affects the interband transition for the OW nanomembrane. In order to study the thermal effect and its influence on the energy band, we prepared a rolled-up nanomembrane with a diameter of 150 μ m and applied higher voltages, and the photoelectric properties were studied in detail. According to previous literature,²⁵ for a rolled-up structure, the radius (R_0) , bending moment (M_0) and certain thickness (t)can be expressed as follows:

$$R_0 = D/M_0 = t/((1+\nu)\Delta\varepsilon)$$
(1)

where *D* is the stiffness of the nanomembrane, ν represents Poisson ratio (0.31 for GaAs²⁶), $\Delta \varepsilon$ is on behalf of the strain gradient. The lattice mismatch between Al_xGa_{1-x}As and GaAs is 4.16×10^{-4} for x = 0.26, corresponding to Al_xGa_{1-x}As lattice constant of $a_2 = 5.6556$ Å and GaAs lattice constant of $a_1 = 5.6533$ Å.²⁷ This means that the lattice distortion between Al_{0.26}Ga_{0.74}As and GaAs is too small and can be neglected. Since Al_{0.26}Ga_{0.74}As and GaAs layers have almost the same lattice constants, the ν value can be considered constant (0.31). Herein, $\Delta \varepsilon$ can be calculated to be ~ 0.204 % for the rolled-up structure with a diameter of 150 μ m. In the present work, we experimentally find that the diameter of the rolled-up nanomembrane changes with the applied bias voltage, and corresponding results are



Fig. 4 Horizontal displacements of points (a), (b), and (c) for the rolled-up structure with a diameter of 150 μ m. Voltages of -3 and -4.5 V were applied. Vertical displacement at -4.5 V is also presented. The inset schematically shows the positionpoints s of (a), (b), and (c).

Table II Horizontal displacements (Dis.) and ratios for points a, b, c under -4.5 and -3 V. Ave. is the abbreviation for average ratio

Points	a	b	С
Dis. (-4.5 V)	1.38 µm	2.39 μm	0.97 µm
Dis. (-3 V)	0.68 µm	0.93 µm	0.41 µm
Ratio	2.03	2.57	2.37
Ave.	~2.32		

demonstrated in Fig. 4. In the horizontal direction, the distance between points a and c shrinks ~ 0.35 μ m due to the diameter change after -4.5 V was applied. Furthermore, the average movement ratio for points a, b, and c under -4.5 V and -3 V coincides well with the square of the voltage ratio (2.25) within error, as shown in Table II. It is worth noting that the square of the voltage ratio is the ratio of amounts of Joule heat produced by applied voltages. The current experimental results indicate that the thermal effect on the rolledup nanomembrane can decrease its diameter. This is mainly because the outer layer of the rolled-up structures contains an AlAs layer, and its larger resistance produces more Joule heat and corresponding temperature gradient increases the bending moment M_0 (see Eq. 1) to shrink the diameter.²⁵ It also can be seen that the vertical direction of the rolled-up structure is obviously affected by the thermal effect, and Fig. 4 demonstrates a linear relationship with vertical displacements of $-0.23 \,\mu\text{m}$, $-0.83 \,\mu\text{m}$, and $2 \,\mu\text{m}$ for points c, b, and a, respectively. The position near the cut-off position of the rolled-up nanomembrane moves downward, and the vertical displacement shows a linear increase with the distance to the cut-off position (Fig. 4). Therefore, the results suggest that the thermal deformation of the tube is cumulative with the distance from the cut-off position.

For a working rolled-up QWIP, the heat produced by current causes an inevitable diameter change, which further changes the energy band. It can be calculated that the redshift within the conduction band for QW₁ is $\sim 8 \times 10^{-4}$ meV, and the blueshift for QW₂ is $\sim 3 \times 10^{-3}$ meV when the applied voltage is -4.5 V. According to the above discussion, the intraband shift of the conduction band for QW₁ is about 0.008 meV/K. Thus, it can be estimated that the temperature increase is ~ 0.1 K under -4.5 V, and the change of band gap can be deduced to be about 0.045 meV (because the rate of change is -0.45 meV/K). It has been illustrated that an applied voltage of -4.5 V can cause deviations of the wave functions to enlarge the band gap to be about 12 meV.⁷ Compared with this value, the thermal effect from the applied voltages leads to negligible band gap change.

Conclusions

Rolled-up nanomembranes have been fabricated by the liftoff method. According to the high-resolution hard x-ray diffraction analysis, we find that the (110) reflection is the Bragg diffraction of two different kinds of atoms whose spacing irregularly changes after rolling, and the other two reflections correspond to Bragg diffractions from identical atoms whose spacing continuously changes after rolling. We measured the temperature-dependent photocurrent spectra of a rolled-up device under different applied voltages and found that the photoresponse of QW under tensile strain is promoted. For a rolled-up device with a diameter of $62 \,\mu m$, the photoresponse of QW1 in tensile strain increases to 2.1 times and the photoresponse of QW₂ in compressive strain decreases to about 65%. We also found that the gap between the ground state and excited state in the conduction band decreases with a rate of ~ 0.008 meV/K and the thermal effect mainly affects the interband shift of the band structure. Furthermore, we showed that the thermal effect of applied voltage on the change of band gap is negligible.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11664-021-08880-1.

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Conflict of interest The authors declare that they have no conflict of interest.

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