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Towards flexible quantum well infrared photodetectors

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ABSTRACT

Quantum well infrared photodetectors (QWIPs) based on GaAs have attracted much attention owing to its matured material growth technique. In order to obey the selection rule of polarization, various grating structures have been attached to planar QWIPs. Recently, we experimentally demonstrated that strained planar QWIPs could be self-rolled up into an out-of-plane tubular geometry so that the polarization selection rule is sufficiently subdued without any extra grating structure. Such self-rolled-up QWIPs show a broadband enhancement of responsivity and detectivity over a wide incident angle. In this paper, both wave-optics and ray-optics simulations are performed to clarify the underlying physics. The well-defined curved QWIPs pave a path towards flexible QWIPs for flexible optoelectronics.

Keywords: Flexible optoelectronics, Infrared photodetectors, QWIPs, Curved QWIPs, Rolled-up QWIPs, Broadband enhancement, Wide-angle enhancement, Rolled-up technology

1. INTRODUCTION

The investigation of flexible electronics has over the last two decades become a distinct subject of research in modern science, engineering and technology.[1,2] With thousands of successful demonstration devices, the scope of this research has expanded to include more challenging but rewarding areas, e.g., flexible integrated photonics[3] and flexible optoelectronics.[4,5] Very recently, we have experimentally fabricated and charactered a three-dimensional

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(3D) tubular quantum well (QW) infrared photodetector (QWIP) based on the so-called rolled-up nanotechnology,[6] which has been demonstrated as an efficient route to versatile optical micro/nanostructures.[7–13] The realization of 3D tubular QWIPs takes the first step towards flexible infrared photodetectors.

Rolled-up 3D tubular QWIPs offer three main advantages over the traditional planar ones. First of all, the polarization selection rule required by the embedded QW is automatically satisfied without any external light coupling structures, which are normally necessary for QWIPs. Secondly, the circular symmetric structure of tubular QWIPs enables omnidirectional detection under a wide incident angle, which is unreachable for planar infrared photodetectors. The third advantage of rolled-up 3D tubular QWIPs is that a wavelength-independent enhancement (approximately 3 times in the wavelength range of 3 to 8 μm) in the photocurrent responsivity is achievable. These advantages provide a lot of benefit to the design of an high-performance infrared focal plane array (FPA) imaging system.

In this paper, we further clarify the underlying physics behind the wavelenght-independent characteristic and the enhancement factor of 3 for the rolled-up 3D tubular QWIPs. The former is clear and unambiguous by checking the dispersion relation of light in rolled-up structures based on wave optics, while based on ray optics the latter is evidence by tracing the light trajectory through them. These results will help with the optimization of rolled-up 3D tubular QWIPs as well as other flexible optoelectronic devices.

2. WAVE OPTICS OF ROLLED-UP QWIPS

In 2006, rolled-up nanotechnology has been adopted into optics.[8] Light emitted from luminescent materials can be confined within the subwavelenght-thin wall of rolled-up structures due to the total internal reflection and a constructive interference, leading to an optical microcavity (see Fig. 1(c)). Since then, numerous luminescent material systems have benefited from this nanotechnology and been manufactured as rolled-up optical microcavities,[14] while various analytical theories and numerical simulations have been developed based on wave optics.[10, 15–17] Unfortunately, these findings are not available for the rolled-up 3D tubular QWIPs recently developed in our institute. By examining the dispersion relation of light in rolled-up structures, this divergence is, however, not surprising.

Dispersion relation $\omega - k$ of light is generally used in wave optics to describe the photonic band structure,[18] where ω is the frequency of light and k its in-plane wave vector. Figure 1(b) shows the dispersion relation for light in rolled-up structures. There is a light line $\omega = ck$ (c is the speed of light), which separates the $\omega - k$ plane into two distinct zones. Light in the zone below the light line takes the form of discrete resonant modes. In this zone, the wavelength of light is close to the wall thickness so that wave optics rules over the behavior of light. In

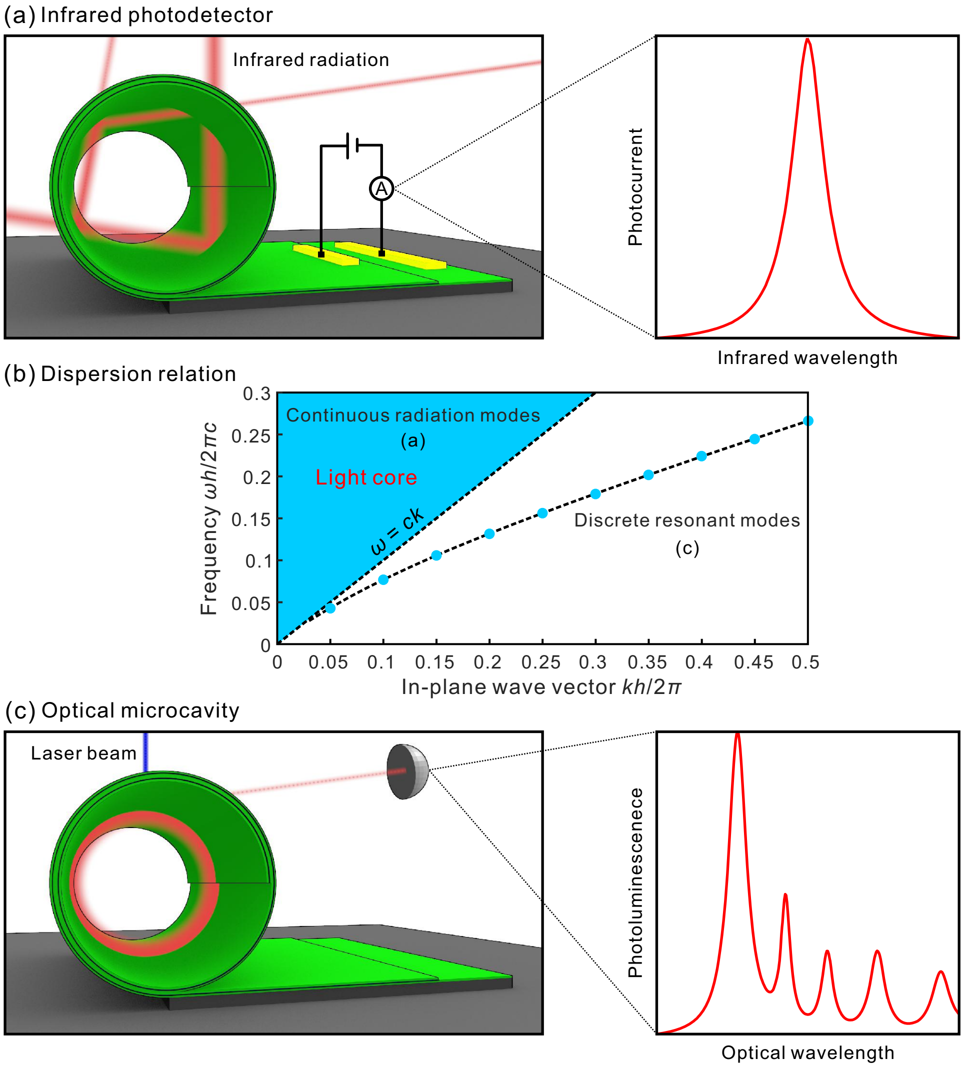

Figure 1. Comparison between rolled-up optical microcavities and rolled-up infrared photodetectors. (a) Sketch of a rolled-up infrared photodetector. Infrared radiation is absorbed as it passes through the thin wall. At the curled part of rolled-up structure, multiple absorbing of the incident infrared radiation is enabled. The resultant photocurrent is recorded with an external circuit. (b) Dispersion relation $\omega - k$ of light in rolled-up structures. Light in rolled-up infrared photodetectors takes the form of a radiation mode when $\omega - k$ is located within the light core bounded by the light line $\omega = ck$, while light in rolled-up optical microcavities becomes a resonant mode when $\omega - k$ is out of the light core. Ray optics rules over light in the light core while it is governed by wave optics. (c) Sketch of a rolled-up optical microcavity. Emitted light within the subwavelenght-thin wall, excited by a laser, travels around the rolled-up structure because of the total internal reflection. Optical resonances occur owing to constructive interferences of the traveling light. The escaped light is collected with an external optical detector.

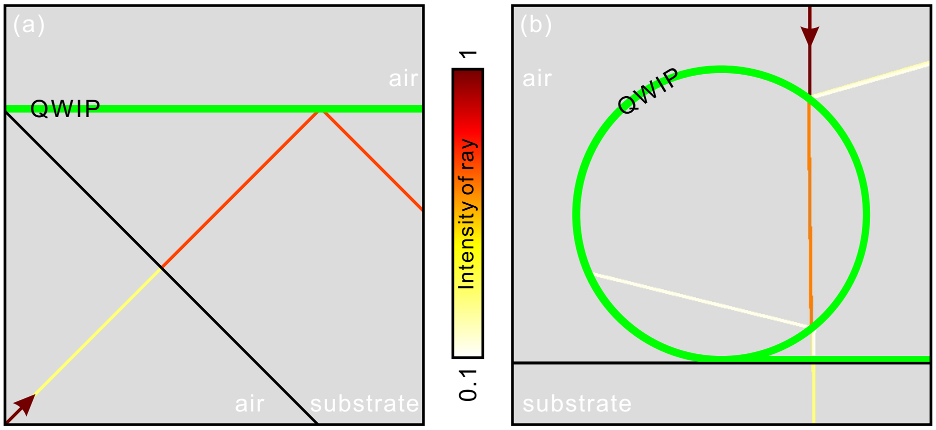

Figure 2. Ray-optics simulations for (a) a 45° edge facet QWIP and (b) a rolled-up QWIP. Light is released according to the experimental conditions, as indicated by the arrow. The intensity of light along its ray trajectory is shown by color.

contrast, light in the zone above the light line (i.e., the so-called light core) is in the form of a radiation mode. Since there is no resonance in this zone, ray optics takes over the light behavior. Now, one can simply identity the behavior of light by examining the zone a rolled-up structure/device is working in.

For rolled-up optical microcavities, the wavelength considered is in the visible or near-infrared spectral range.[19,20] It is close to the wall thickness. As a result, the dispersion relation of light in rolled-up optical microcavities is out of the light core, so that resonant modes are the working modes, as shown in Figs. 1(b) and 1(c). The wall thickness of rolled-up QWIPs is the same as that of the rolled-up optical microcavities. However, the working wavelength of QWIPs is in the mid- or far-infrared spectral range, which is far away from the wall thickness. Therefore, the dispersion relation of light in rolled-up QWIPs is located within the light core where there is no resonance, as shown in Figs. 1(a) and 1(b). A direct consequence of this non-resonance is the wavelenght-independent characteristic in rolled-up 3D tubular QWIPs.

3. RAY OPTICS OF ROLLED-UP QWIPS

The enhanced photocurrent responsivity in rolled-up 3D tubular QWIPs is believed to originate from multiple reflection of the incident infrared light.[6] To confirm this enhancement mechanism, numerical simulations based on wave optics were carried out. From the wave-optics simulations, the stationary electric field distributions can be obtained. According to a quantitative analysis, the photocurrent responsivity is proportional to the average intensity of the stationary electric field. It was found that the enhancement ratio of the average electric field intensity is 3.4, which coincides well with the experimental enhancement factor of 3.1. Therefore, the wave-optics simulations for rolled-up QWIPs were thought to be good, although the physical picture is blurred.

As discussed above, the dispersion relation of light in rolled-up QWIPs is located in the light core, where ray optics takes over the behavior of light. Therefore, ray-optics simulations for rolled-up QWIPs are performed in this paper, and the results are summarized in Fig. 2. For the traditional planar QWIP, light is launched perpendicular to its 45° edge facet in order to obey the polarization selection rule, as shown in Fig. 2(a). As light propagates along the ray trajectory, it is absorbed once by the planar QWIP. On contrast, light can be released over a wide-angle range for rolled-up QWIPs. However, only normal incidence of light is considered for infrared FPA applications, as shown in Fig. 2(b). Light is absorbed several times by the rolled-up QWIP due to a multiple *inward* reflection, as we believed. Moreover, one can now clearly see from the ray-optics simulations that there are just 3 times absorption, neither 2 nor 4, limited by a maximum of 3 times *outward* reflections. Anyway, based on ray optics, the multiple reflection in rolled-up QWIPs is confirmed and the enhancement factor of 3 is evident.

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REFERENCES

[1] Rogers, J. A., Someya, T., and Huang, Y., "Materials and mechanics for stretchable electronics," *Science* **327**, 1603 (2010).

[2] Rogers, J. A., Lagally, M. G., and Nuzzo, R. G., "Synthesis, assembly and applications of semiconductor nanomembranes," *Nature (London)* **477**, 45 (2011).

[3] Hu, J., Li, L., Lin, H., Zhang, P., Zhou, W., and Ma, Z., "Flexible integrated photonics: where materials, mechanics and optics meet," *Opt. Mater. Express* **3**, 1313 (2013).

[4] Park, S.-I., Le, A.-P., Wu, J., Huang, Y., Li, X., and Rogers, J. A., "Light emission characteristics and mechanics of foldable inorganic light-emitting diodes," *Adv. Mater.* **22**, 3062 (2010).

[5] Shahi, S., "Photovoltaics: Flexible optoelectronics," *Nat. Photonics* **4**, 506 (2010).

[6] Wang, H., Zhen, H., Li, S., Jing, Y., Huang, G., Mei, Y., and Lu, W., "Self-rolling and light-trapping in flexible quantum well-embedded nanomembranes for wide-angle infrared photodetectors," *Sci. Adv.* **2**, e1600027 (2016).

[7] Schmidt, O. G. and Eberl, K., "Nanotechnology: Thin solid films roll up into nanotubes," *Nature (London)* **410**, 168 (2001).

[8] Kipp, T., Welsch, H., Strelow, C., Heyn, C., and Heitmann, D., “Optical modes in semiconductor microtube ring resonators,” *Phys. Rev. Lett.* **96**, 077403 (2006).

[9] Mei, Y., Huang, G., Solovev, A. A., Ureña, E. B., Mönch, I., Ding, F., Reindl, T., Fu, R. K. Y., Chu, P. K., and Schmidt, O. G., “Versatile approach for integrative and functionalized tubes by strain engineering of nanomembranes on polymers,” *Adv. Mater.* **20**, 4085 (2008).

[10] Strelow, C., Schultz, C. M., Rehberg, H., Sauer, M., Welsch, H., Stemmann, A., Heyn, C., Heitmann, D., and Kipp, T., “Light confinement and mode splitting in rolled-up semiconductor microtube bottle resonators,” *Phys. Rev. B* **85**, 155329 (2012).

[11] Li, S., Ma, L., Zhen, H., Jorgensen, M. R., Kiravittaya, S., and Schmidt, O. G., “Dynamic axial mode tuning in a rolled-up optical microcavity,” *Appl. Phys. Lett.* **101**, 231106 (2012).

[12] Ma, L., Li, S., Fomin, V. M., Hentschel, M., Götte, J. B., Yin, Y., Jorgensen, M. R., and Schmidt, O. G., “Spin-orbit coupling of light in asymmetric microcavities.,” *Nat. Commun.* **7**, 10983 (2016).

[13] Yin, Y., Li, S., Böttner, S., Yuan, F., Giudicatti, S., Saei Ghareh Naz, E., Ma, L., and Schmidt, O. G., “Localized surface plasmons selectively coupled to resonant light in tubular microcavities,” *Phys. Rev. Lett.* **116**, 253904 (2016).

[14] Wang, J., Zhan, T., Huang, G., Chu, P. K., and Mei, Y., “Optical microcavities with tubular geometry: properties and applications,” *Laser Photonics Rev.* **8**, 521 (2014).

[15] Li, S., Ma, L., Böttner, S., Mei, Y., Jorgensen, M. R., Kiravittaya, S., and Schmidt, O. G., “Angular position detection of single nanoparticles on rolled-up optical microcavities with lifted degeneracy,” *Phys. Rev. A* **88**, 033833 (2013).

[16] Fang, Y., Li, S., and Mei, Y., “Modulation of high quality factors in rolled-up microcavities,” *Phys. Rev. A* **94**, 033804 (2016).

[17] Lan, Y., Li, S., Cai, Z., Mei, Y., and Kiravittaya, S., “Semi-analytical calculation of resonant modes in axially asymmetric microtube resonators,” *Opt. Commun.* **386**, 72 (2017).

[18] Joannopoulos, J. D., Johnson, S. G., Winn, J. N., and Meade, R. D., [*Photonic crystals: Molding the flow of light*], Princeton University Press, New Jersey, 2nd ed. (2008).

[19] Böttner, S., Li, S., Trommer, J., Kiravittaya, S., and Schmidt, O. G., “Sharp whispering-gallery modes in rolled-up vertical SiO2 microcavities with quality factors exceeding 5000,” *Opt. Lett.* **37**, 5136 (2012).

[20] Böttner, S., Li, S., Jorgensen, M. R., and Schmidt, O. G., “Vertically aligned rolled-up SiO2 optical microcavities in add-drop configuration,” *Appl. Phys. Lett.* **102**, 251119 (2013).